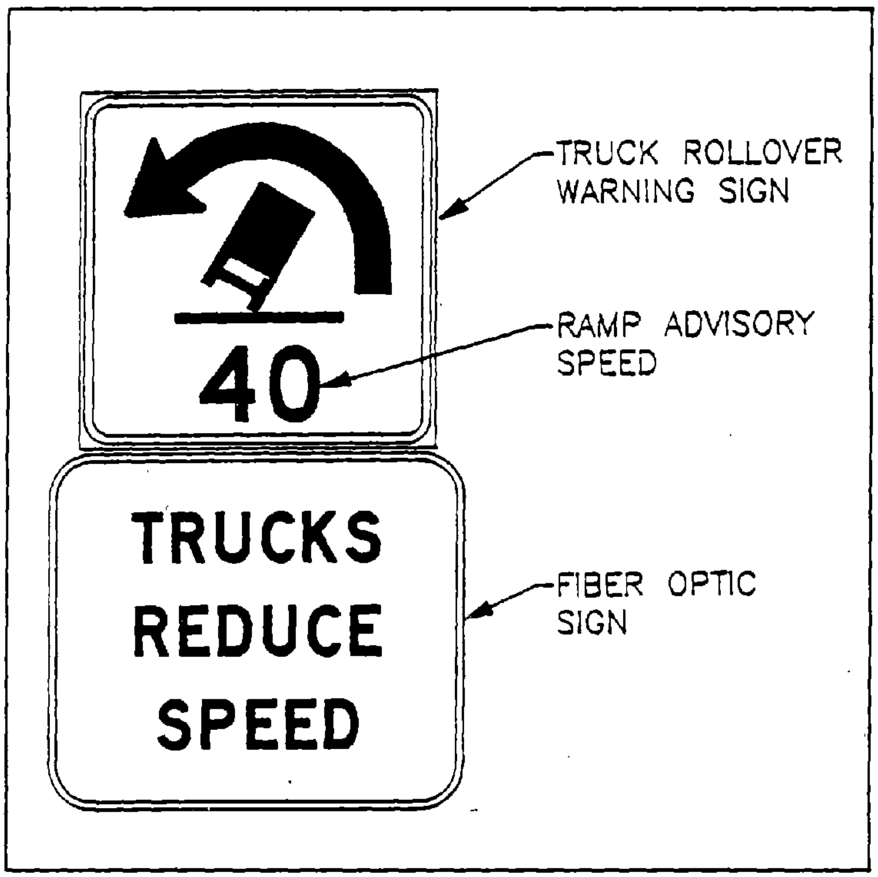
Feasibility of an Automatic Truck Warning System

FHWA-RD-93-039

September 1993



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Federal Highway Administration

Research and Development
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FOREWORD

This report will be of interest to highway safety engineers responsible for the application of systems to reduce truck rollover accidents on curved ramps from freeways. The basic study was directed at the ramps on the Capital Beltway located in Maryland and Virginia.

The results of this research indicate that the installation of an automatic truck warning system is currently cost-effective for ramps that have one or more truck rollover accidents within a 5-year period. Based on the concept of an in-road detection/warning system, three prototype truck warning systems are being installed on the Capital Beltway: two in Virginia and one in Maryland. The operations of these systems will be evaluated in the next 3 years.

Two copies of this report are being sent to each region, and six copies are being sent to each division office. At least four of these copies sent to the division should be sent to the State highway agency by the division office.

Lyle Saxton

Lyle Saxton, Director
Office of Safety and Traffic Operations
Research and Development

NOTICE

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16. Abstract

One of the identified truck accident types that occur on curved exit ramps at interchanges is truck rollover. A truck will overturn or rollover if the lateral acceleration imposed upon it as it travels around a curve of a certain radius and superelevation is greater than allowable given its loading condition. Also, there is a speed at which rollover will occur. This report deals with an automatic warning system to prevent truck rollover.

Within the study, three different options were identified and evaluated for feasibility. Of the three, the option selected for further definition and cost-effectiveness analyses was an inroad detection/warning system. The system consists of two detection stations upstream of the curve with the combined ability to detect a truck speed, weight, and height threshold. The warning system is a combination of a static warning sign and a fiber-optic warning message sign, which would be activated if the controller determined that the truck would be operating at the rollover threshold speed or faster by the time it reached the point of curvature.

This report provides the details of the design, its costs, and its cost-effectiveness. Also, design plans and specifications were prepared for three installations on the Capital Beltway in Maryland and Virginia.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	ac
ha	hectares	2.47	acres	mi^2
km^2	square kilometers	0.386	square miles	
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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CHAPTER 1. INTRODUCTION

BACKGROUND

Truck accidents on urban freeways occur more frequently at interchanges than at any other location. Most of the truck accidents that occur on interchange ramps do so on off-ramps. Overturned truck accidents on off-ramps at interstate interchanges represent 5 out of every 100 fatal truck accidents.[1]

A prominent accident type at interchanges is the large truck overturning or rollover on a curved ramp. Rollover accidents occur under the conditions of a sharp radius curve preceded by conditions that encourage higher than safe approach speeds.

The consequences of truck rollover accidents can be very costly, particularly in urban locations. These accidents usually result in large losses due to fatalities and injuries, vehicle and roadway damage, and traffic delays. The situation is even more complicated and losses even greater when trucks carrying combustible or hazardous cargo are involved in such accidents.

Currently, the typical countermeasure to prevent truck rollover accidents, aside from changes to the ramp geometrics, has been to deploy various warning signs. In addition to the standard exit speed or the ramp speed warning sign (sign W13-2 and W13-3 in the *Manual on Uniform Traffic Control Devices*) and signs used for curves (i.e., large arrows, chevron alignment signs, etc.), some States use a special rollover warning sign that depicts a tipping truck with a speed advisory.[2] However, these static devices can go undetected or ignored especially if the need for the low speed is not apparent. To improve the attention-getting value of these warning signs, flashing lights have been added to the sign assembly. And, to enhance the capability of the system by directing the warning to specific trucks that have the potential to rollover, experimentation with speed-actuated flashing lights has been undertaken. In a recent study of such a system, where the researchers manually activated flashing lights when the recorded speed (tape switches on the road) exceeded the predetermined maximum speed, the results suggested "...that a flashing truck speed advisory warning sign activated for tractor-trailers that are likely to exceed the maximum safe speed is more effective than a similar but nonflashing warning sign in reducing speeds of the fastest tractor-trailer trucks at the critical curve sections of the freeway ramps.... These results suggest that a conspicuous rollover-warning sign that is clearly directed toward individual truck drivers would be more effective in reducing truck speeds than current advisory speed signs."[3] In that experiment, the flashing lights were manually activated based on truck speed alone. Since truck rollover is dependent upon other truck characteristics, including axle load and center of gravity height, a system that would detect trucks that might rollover based on various parameters and would automatically activate the warning system would be a desirable improvement.

This report deals with a countermeasure for preventing or reducing rollover accidents at interchanges. Specifically, the countermeasure involves an automatic warning system that would help truck drivers take timely evasive action. The warning system would be activated if a truck, based on its load conditions and speed, may rollover if its speed is not reduced.

PURPOSE OF THE STUDY

The objectives of this study are:

1. To develop the system requirements for a truck speed-activated warning sign when high approach speeds are measured for high-potential rollover trucks, and identify the hardware and software available to install such a system.

2. To estimate equipment, installation, and operational costs for installation of a truck speed warning system at a ramp with great potential for high speed accidents on the Capital Beltway in Maryland and Virginia.

3. To determine the cost-effectiveness of installing a truck speed warning system at all ramps with a high speed potential for truck rollover accidents on the Capital Beltway in Maryland and Virginia.

In addition to these stated objectives, design plans were prepared for installation of the selected system at three ramps, two in Virginia and one in Maryland.

CHAPTER 2. TRUCK ROLLOVER PROBLEM ON FREEWAY RAMPS

INFLUENCING FACTORS

The rollover of trucks on interchange ramps occur due to a number of reasons. The major reason for such occurrences is driving at a speed that exceeds a certain threshold speed, which is governed by the specific roadway and truck characteristics. In a study on the stability and control of heavy-duty trucks on ramps, it was reported that problems that cause accidents fall into two categories.[4] The first category of problems describe inherent limitations in truck stability and control qualities. The second category describes problems in which truck driver actions appear to involve misjudgments. In the study, five typical problem ramp situations were investigated as case studies. The problems highlighted by these case studies were also found to describe some of the principal causes of truck rollover accidents on ramps. Brief descriptions of these case studies are given below:

- Case Study No. 1: Excessive side friction factor given the roll stability limits of the truck. Another interpretation of this cause in terms of highway conditions is poor transition of superelevation.

- Case Study No. 2: Assumption by truckers that the ramp advisory speed does not apply to all curves on the ramp. This occurs when there are abrupt curvature changes in compound curves on loop ramps.

- Case Study No. 3: Deceleration lane lengths are deficient for trucks, resulting in excessive speeds at the entrance of sharply curved ramps.

- Case Study No. 4: Lightly loaded truck tires are sensitive to pavement texture in avoiding hydroplaning on high-speed ramps. This condition often leads to stability problems for empty trucks, resulting in jackknife and other non-rollover accidents.

- Case Study No. 5: Curbs placed on the outer edge of the ramp that trip and overturn articulated truck combinations. This practice is not recommended in the *Policy on Geometric Design of Highways and Streets*.[5]

Another complicating factor is the lateral shift of the cargo being carried in the truck. This occurs when tanker trucks with liquid cargo or trucks with hanging meat negotiate ramp curves.

NATIONAL ACCIDENT DATA

Unfortunately, there are few accident statistics related to the frequency of truck rollover accidents nationwide. In one study, data on truck rollover accidents from eight States were collected and summarized.[4] Although the samples used were not nationally representative, the statistics obtained from them, and shown in table 1, demonstrate the truck rollover problem. Statistics on rollover accident location on ramps indicated that most of these accidents (35 percent) occurred in the first quarter of the ramp. A large number of these accidents were also identified as being caused by load/cargo shift.

Table 1. Accident characteristics for truck rollover accidents at ramps.[4]

		STATE NO.							
		1	2	3	4	5	6	7	8
Approximate Number of Overturning Truck Accidents Occurring at Ramps (Annually)		23	35	88	24	-	11	-	-
		PERCENTAGES							
Truck Type:	Straight Truck	-	-	40	38	0	11	18	0
	Single Trailer	-	-	42	62	100	56	82	86
	Double Trailer	-	-	10		0	33	0	14
Injury Severity:	Fatal	3	0	1	0	0	0	10	0
	Injury	62	43	59	62	55	65	40	43
	PDO	35	57	40	38	45	35	50	57
Light Condition:	Daylight	-	46	70	85	70	67	70	82
Weather:	Clear	-	77	79	85	100	67	90	66
	Rain	-	20	11	15	0	33	10	25
	Snow	-	3	9	0	0	0	0	9
Road Surface:	Dry	-	69	72	83	95	76	90	66
	Wet	-	29	16	7	5	24	10	25
	Snow/Ice	-	3	12	0	0	0	0	9
Load Shifting		-	-	12	35	55	66	60	43
Struck Curb or Island		-	37	1	0	0	0	10	0

Statistics from the Federal Highway Administration's Office of Motor Carrier Safety indicate that of the 35,341 truck accidents reported to that agency in 1989, 3,114 involved an overturned truck (about 0.8 percent). Furthermore, that agency estimates that 75 percent of these accidents occurred on ramps.

TRUCK ROLLOVER OCCURRENCE ON CAPITAL BELTWAY RAMPS

The Capital Beltway has a total of 41 interchanges, 14 in Virginia and 27 in Maryland. Ramp truck accident data for both Virginia and Maryland sections of the beltway were reviewed for the years 1986 through 1989. Data on accidents occurring in the Virginia section of the beltway were extracted from copies of police accident report forms obtained from the Virginia Department of Transportation. For the Maryland section of the beltway, accident data were extracted from a partial accident data base provided by the Maryland Department of Transportation.

From the accident statistics reviewed, ramp locations at which truck rollover occurrence is most frequent were identified as problem locations. This criterion for identifying problem locations does not account for exposure or the amount of truck travel that occurs at each ramp. The justification for this approach is that the only additional information that would be generated by considering exposure is the ability to compare ramps based on accident rates, which is not really helpful to reach the goal of this project. For example, a ramp may experience a high rollover accident rate but a low rollover accident frequency. Therefore, in any attempt to reduce the total frequency of such accidents, it is common sense that countermeasures must first be applied at high accident frequency locations. The goal of this project is to minimize the number of truck rollover occurrences and their consequences, such as heavy traffic congestion and delay.

Tables 2 and 3 show a summary of the truck rollover occurrence statistics for those Capital Beltway interchange ramps that experienced at least one rollover accident in the analysis period. As can be seen in the two tables, a truck rollover accident is a relatively rare event. Only five of the Virginia ramps had two rollovers for a 3-year period and only one ramp in Maryland had more than one rollover in a 5-year period. The loop ramp identified in figure 1 as ramp no. 5 had six rollovers. It should be noted that a new ramp (no. 9) has been installed at this interchange, which has significantly reduced the truck traffic for ramp no. 5, and this ramp is no longer a truck rollover problem site.

Table 2. Truck rollover occurrence on Capital Beltway ramps – Virginia.

Virginia Section of Beltway: 1986 to 1989

Interchange	Total No. of Occurrences	Highest Occurrence on One Ramp
I–95	2	2
VA–620	2	1
VA–236	2	1
I–66	5	2
VA–7	2	2
VA–123	3	2
GWMP	2	2

Table 3. Truck rollover occurrence on Capital Beltway ramps – Maryland.

Maryland Section of Beltway: 1985 to 1990

Interchange	Total No. of Occurrences	Highest Occurrence on One Ramp
MD–4	1	1
MD–202	1	1
MD–450	1	1
I–95	15	6
MD–97	1	1
MD–190	1	1

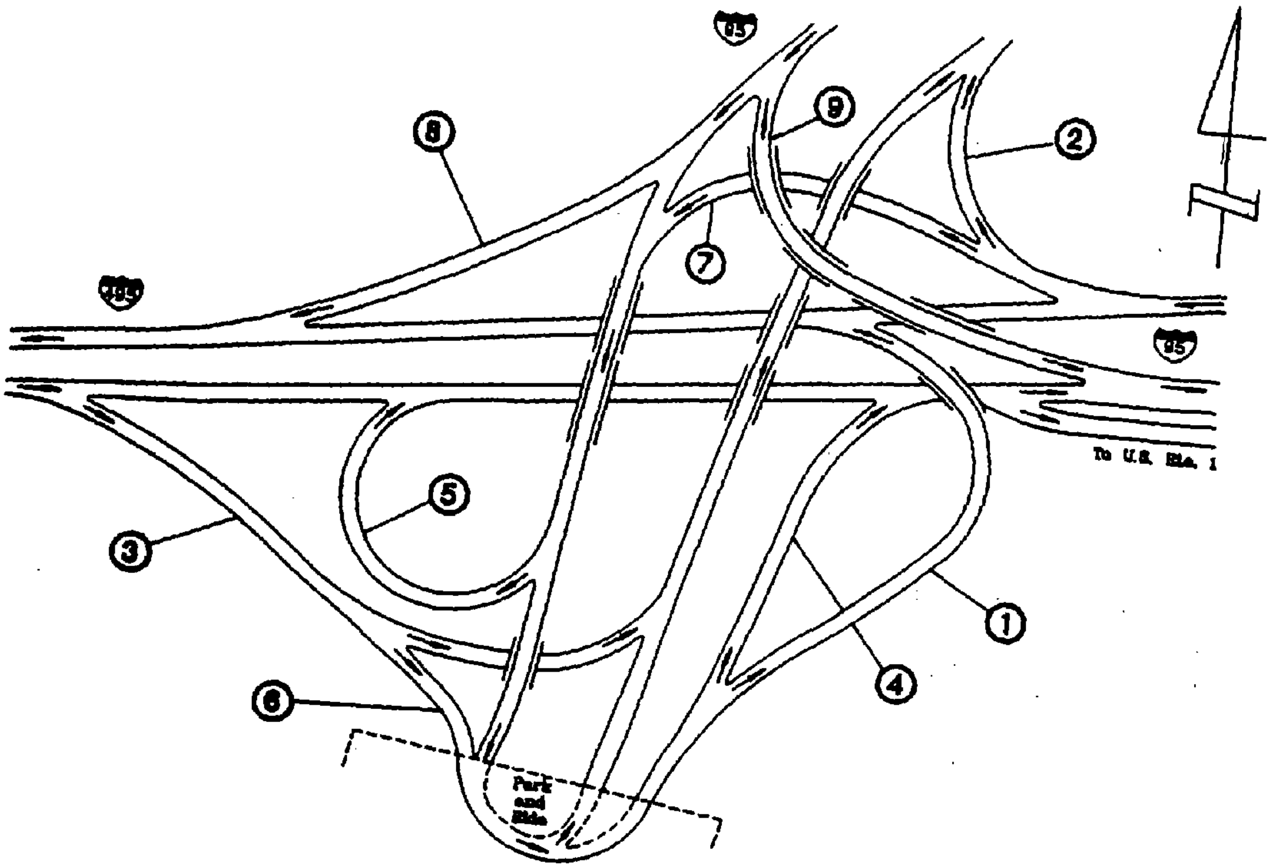


Figure 1. Interchange at I-95 and I-495 in Maryland.

CHAPTER 3. IDENTIFICATION OF TRUCKS WITH HIGH ROLLOVER POTENTIAL

LITERATURE REVIEW

Studies of the rollover process employ static and/or dynamic approaches. The tilt-table method represents the static approach.[6] By statically tilting the examined truck to the point where it almost rolls over, the equivalent driving conditions that could have caused rollover can then be computed. Indeed that approach lacks the dynamics involved in real-life rollover, but its accuracy far exceeds any level of precision that can be achieved in an actual test, not to mention the simplicity of the setup. The dynamic approach usually utilizes computer simulations, such as the Yaw/Roll model developed by University of Michigan Transportation Research Institute (UMTRI).[7] When the detailed set of required input data is carefully procured and employed, the results of that model have been found to be consistent with those acquired on the test track.

The process of the rollover, the various ways of modeling it, and the different parameters involved and their significance, have all been extensively studied in the past (see references 8, chapter 19, and 9). The contribution of each parameter to roll stability, or the effects it might have on diminishing this stability are discussed. The process of rollover is described in detail, and some typical cases are studied. One of the more complicated aspects of the rollover process, which can only be analyzed dynamically, is the effect of moving load (slosh and slide) [see reference 8, chapter 19]. Different types of moving loads and the geometry by which they are contained (especially liquids), are discussed to establish ways for evaluating the reduction effect these have on the roll performance of the truck.

Parameters that have influence on the rollover process in general and the stability of the trucks in particular are discussed in references 10, 11, and 12. The first reference was also used as the theoretical foundation for UMTRI's set of "Simplified Models," which is a set of computer models used to analyze the dynamic behavior of heavy trucks. In these studies, the parameters that have a critical effect on the rollover of trucks are emphasized, and the influence that variations in their values have on rollover is studied.

Identical units, when combined differently to create various heavy truck configurations, will demonstrate distinct dynamic behavior. The impacts that the various configurations have on truck safety are thoroughly discussed in reference 13. Innovative dollies and their contribution to the stability of the heavy duty truck combinations are also discussed.

The literature mentioned above pertains mainly to the dynamics of the rollover process, and how it is affected by various truck parameters. The link between rollover and the "landscape" (the immediate implications that the design and geometry of highway ramps have on the stability of trucks) have been studied in the course of the works presented in references 14, 15, and 16. One of the most significant findings was that "...highway design in the U.S. ... does not take sufficiently into account the special maneuvering limitations of heavy trucks. The most fundamental of those are low resistance to rollover..."[15] Even a truck that is considered safe and stable could rollover due to some ramp geometry features if the driver is not given a clear and unmistakable warning far enough in advance.

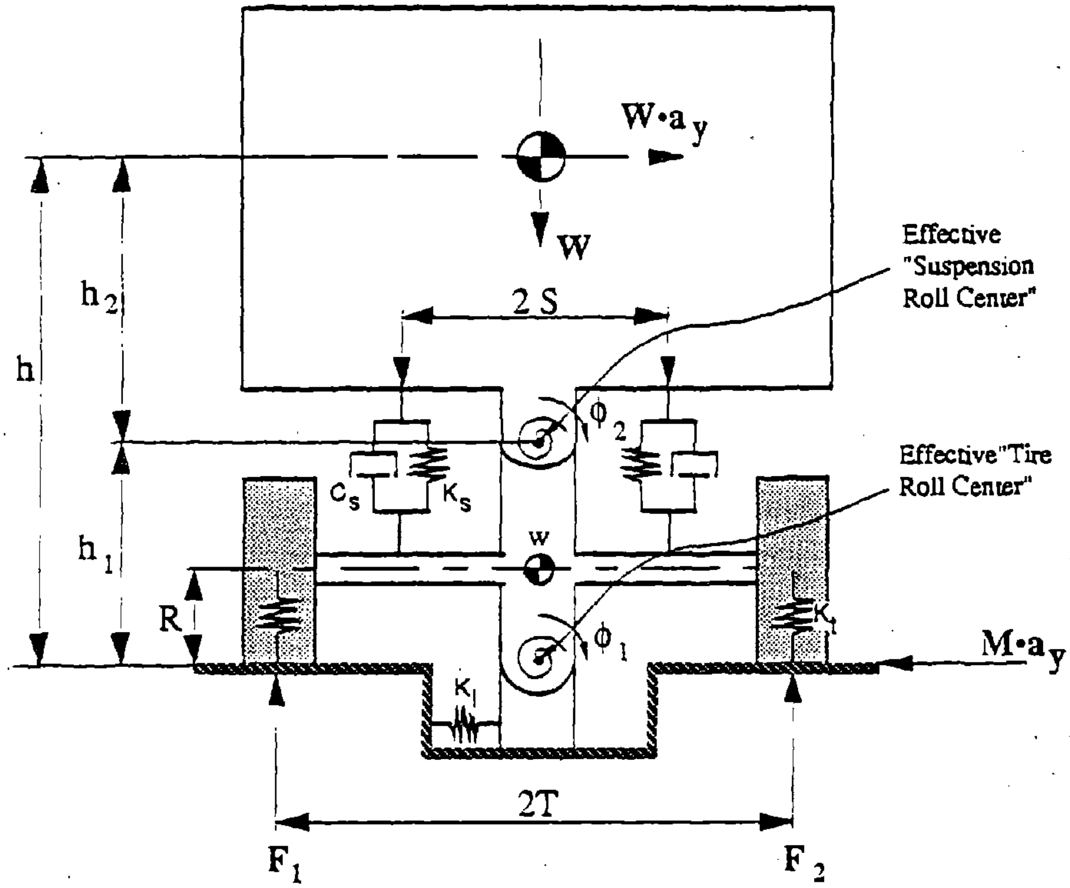
THE ROLLOVER PROCESS

Truck rollover occurs when the lateral component of the acceleration it is subjected to exceeds a certain level called the "rollover threshold." The lateral traction forces of the tires are coupled with the force induced by the acceleration to produce an overturning moment that causes the truck to rollover.

A typical model of a rolling truck usually can be conceptualized as composed of three main segments: the unsprung mass that includes the axle and the tires, the sprung mass that is suspended and tilted, and the suspension which joins the two. The unsprung mass is composed of a nondeformable axle that rests on the ground via two tires. The tires have certain vertical and lateral flexibility. The suspension has vertical stiffness and damping properties, and it defines some roll center around which the sprung mass rolls when subjected to a lateral acceleration. The location of the roll center is virtual, and is determined by the type of suspension (leaf, coil, air springs, etc.) and its geometry. This concept can be employed to model the rolling truck as a set of masses, springs, and dampers, and is shown in figure 2. It describes a "collapsed" model, as a single lumped section suspended on one axle. Rollover will be discussed hereafter assuming an individual section, but one should bear in mind that when a truck is to be evaluated, there are as many sections as there are axles (or suspension units).

The overturning moment that acts to roll the truck over is $W \cdot a_y \cdot h$ (a_y is in terms of a fraction of the gravitation "g"). The restoring moment that opposes it to prevent rollover, is the one established by the deflection of the suspension springs and the deflection of the tires. During this process, load is being transferred from one side (the "inside" of the turn) to the other (the "outside" of the turn).

Under an increasing level of lateral acceleration (a_y), the sprung mass that is suspended over the unsprung mass by the suspension, tilts through roll angle ϕ_2, relative to the unsprung mass. That rotation is performed around the suspension roll center, which is defined by the geometry of the suspension. The "outbound" spring is compressed, while the "inbound" one expands. Under these conditions, a restoring moment that is a roll angle dependent and works toward straightening the sprung mass is generated. At the



w — Unsprung weight

W — Sprung weight

T — Half the tires track

S — Half the suspension springs track

a_y — Lateral acceleration (as fraction of g)

$\emptyset_1$ — Roll angle of unsprung weight

$\emptyset_2$ — Roll angle of sprung weight

F_1, F_2 — Reaction forces in the tires

R — Unsprung weight gravity center height (radius of tire)

h_1 — Sprung weight roll center height

h — Sprung weight gravity center height

h_2 — $= h - h_1$

C_s — Suspension damping

K_s — Suspension stiffness

K_t — Tire vertical stiffness

K_l — Tire lateral stiffness

Figure 2. Truck roll model.

same time, due to the lateral load transfer caused by the roll process, and the compliance of the tires (K_t), the outer tire settles down (F_2 is increased) as the load of the inner one loosens (F_1). The sinking tire on one side and the eased-off tire on the other side cause the axle (the unsprung mass) to rotate through roll angle ϕ_1. It can be shown that the roll center about which ϕ_1 occurs, lies approximately at ground level. The significance of the two roll angles from the statistical stability aspect is that they both act towards bringing the mass center of the truck beyond its track, and facilitate the rollover. Both vertical compliances, the one of the tire (K_t) and the one of the suspension (K_s), are acting during the roll process in a coupled manner to create roll stiffness around the roll axes ($K_{\phi 1}$ and $K_{\phi 2}$, respectively).

At any time during the roll process (as long as both tires are on the ground), it can be shown by equilibrium of moments that the following relation holds[1]:

$$a_y = \frac{-W \cdot h + K_{\phi 2} \cdot \frac{h}{h_2} + B \cdot C \cdot \phi}{W \cdot h - W' \cdot h_1 - A \cdot C} \tag{1}$$

For a given roll angle, the higher the "required" a_y is, the more stable the truck will be. In equation (1), W' is the portion of W that is suspended by the suspension for which the equilibrium applies; ϕ is the roll angle of the sprung mass relative to the ground (absolute roll angle, not ϕ_2 that is relative to the unsprung mass); and A, B, and C are constant expressions. The equations for ϕ, A, B, and C are as follows:

$$A = \frac{W' \cdot h_1 + w \cdot R}{K_{\phi 2} \cdot \frac{h}{h_2} - W' \cdot h_1 - w \cdot R + 2 \cdot K_t \cdot T^2} \tag{2}$$

$$B = \frac{K_{\phi 2} \cdot \frac{h}{h_2}}{K_{\phi 2} \cdot \frac{h}{h_2} - W' \cdot h_1 - w \cdot R + 2 \cdot K_t \cdot T^2} \tag{3}$$

$$C = W' h_1 - K_{\phi 2} \cdot \frac{h}{h_2} \tag{4}$$

$$\phi = \phi_1 + \frac{h_2}{h} \phi_2 \tag{5}$$

---

[1] Full development of the equations can be found in reference 10.

The lateral load transfer that takes place during the roll process and is used in the above equilibrium equations is formulated:

$$\Delta F_z = K_t \cdot T \cdot \phi_1 \tag{6}$$

To emphasize what was previously said: the above set of equilibrium equations of moments is per axle. There is a different set of such equations for each axle; therefore, the total restoring roll moment of the truck is the combination from all the individual axles. As the truck rolls, the restoring moment, which is dependent upon roll angle, increases. This enables a total positive restoring moment, thus maintaining the truck at a stable state. When the roll angle reaches a value that causes the load transfer to be equal to the axle load, that means that the inner wheel has zero load and is lifted off the ground, then the above set of equations is not valid anymore. Under these circumstances, the particular suspension has saturated its capability to generate restoring moment. It has reached some maximum value that remains constant now, regardless of the roll angle. If the roll angle increases now, only the rest of the suspensions (providing they have not saturated yet) will be able to provide additional restoring moment. Another destabilizing factor that rises when the balance of moments is examined, is the contribution to the overturning moment by the increasingly inclined mass. It acts like a "negative" spring: the more tilt there is, the higher the overturning moment.

In the above described terms of equilibrium of moments, a comprehensive roll response of one axle (one "collapsed section") is shown in figure 3.

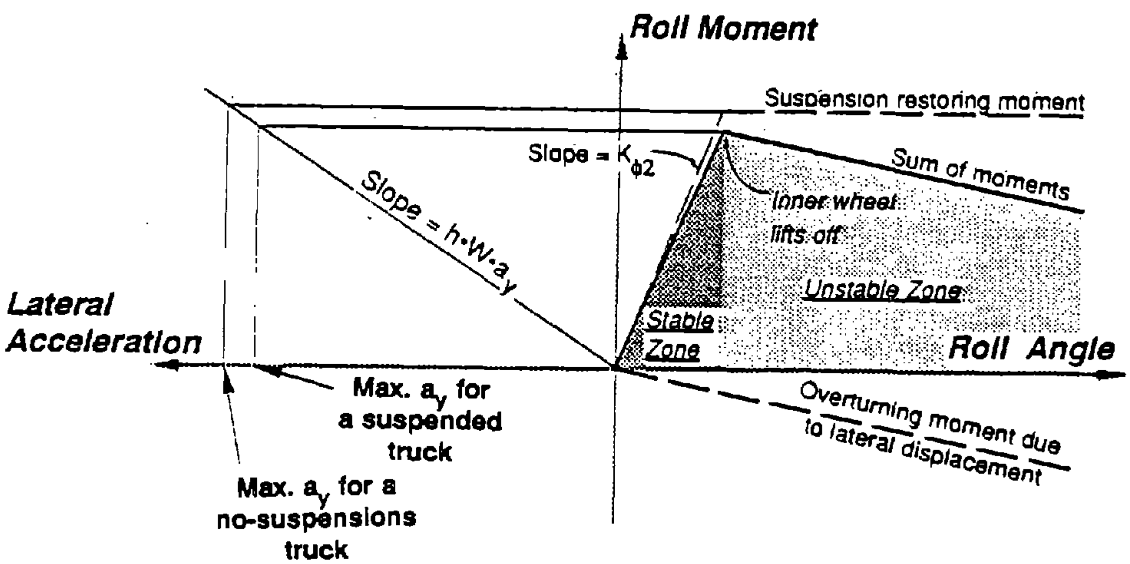


Figure 3. Roll response - single suspension.

The maximum endurable lateral acceleration by that particular suspension before it turns unstable is denoted on the left axis. On this lateral acceleration axis, the influence of the rolling motion on the roll stability of the truck is readily visible: the Max. a_y value for a rolling vehicle is lower than the one for a no-suspensions truck (a stiff box). That is because of the negative slope due to lateral displacement. Again, only one "collapsed section" is shown in figure 3. The rollover threshold of the whole truck should be evaluated based on the roll response plot that combines all the suspensions. Such a graphic description of the roll response that combines all the suspensions for a three-axle truck is presented in figure 4. Initially, all the suspensions have increased contribution to the restoring moment as the truck rolls. First, the trailer's suspension saturates and keeps a constant moment; at this point the trailer's wheels lift off. After a while, the rear suspension of the tractor saturates, and its wheels lift off. Now the only suspension left on the ground is the steering axle, but it is very compliant. The constantly increased overturning moment due to lateral displacement overcomes the total restoring moment, and the slope of the sum of moments turns negative right after the tractor's rear wheel lifted off. The vehicle is now unstable and it will rollover by itself even if the external source of lateral acceleration stops growing.

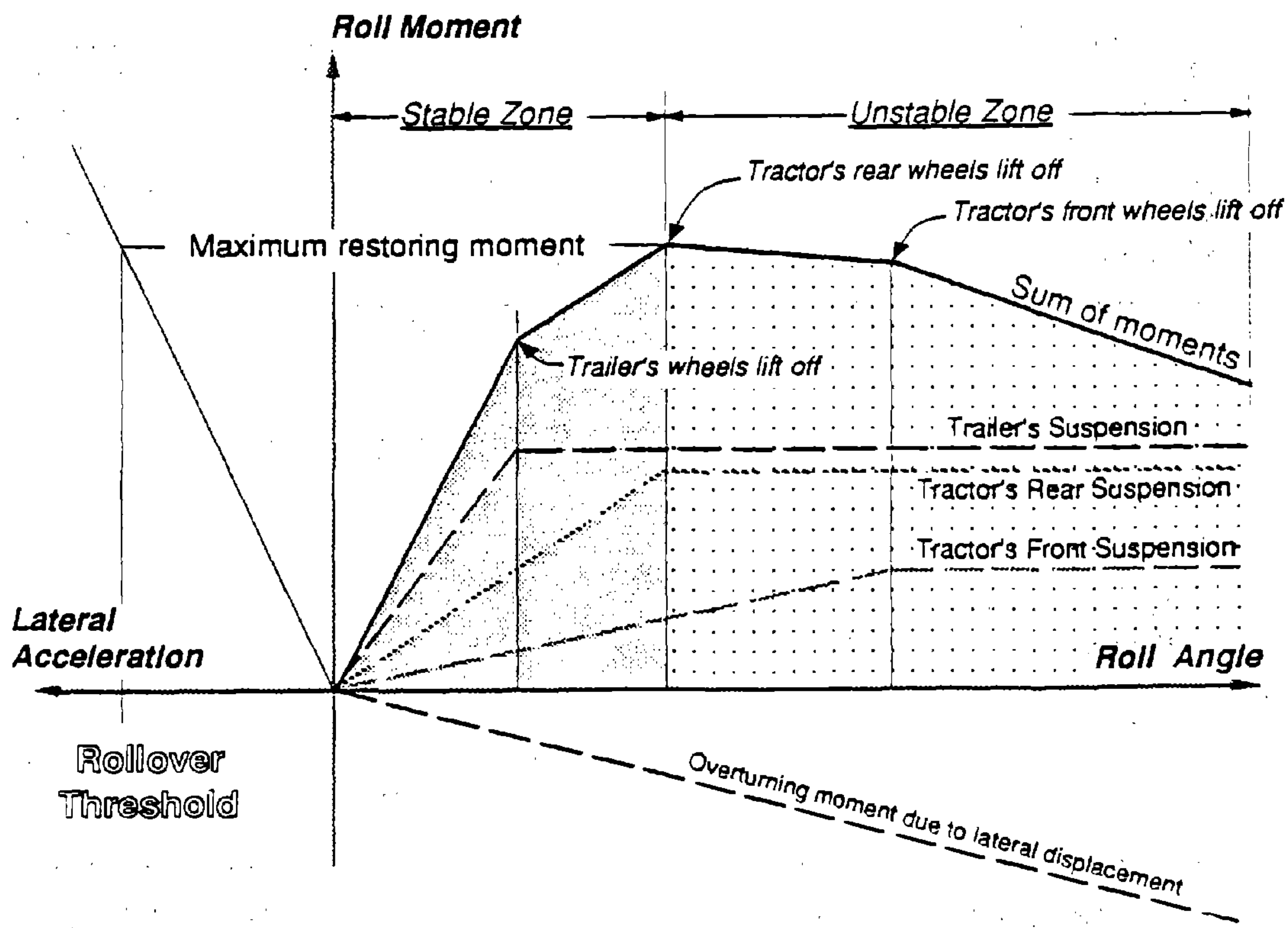
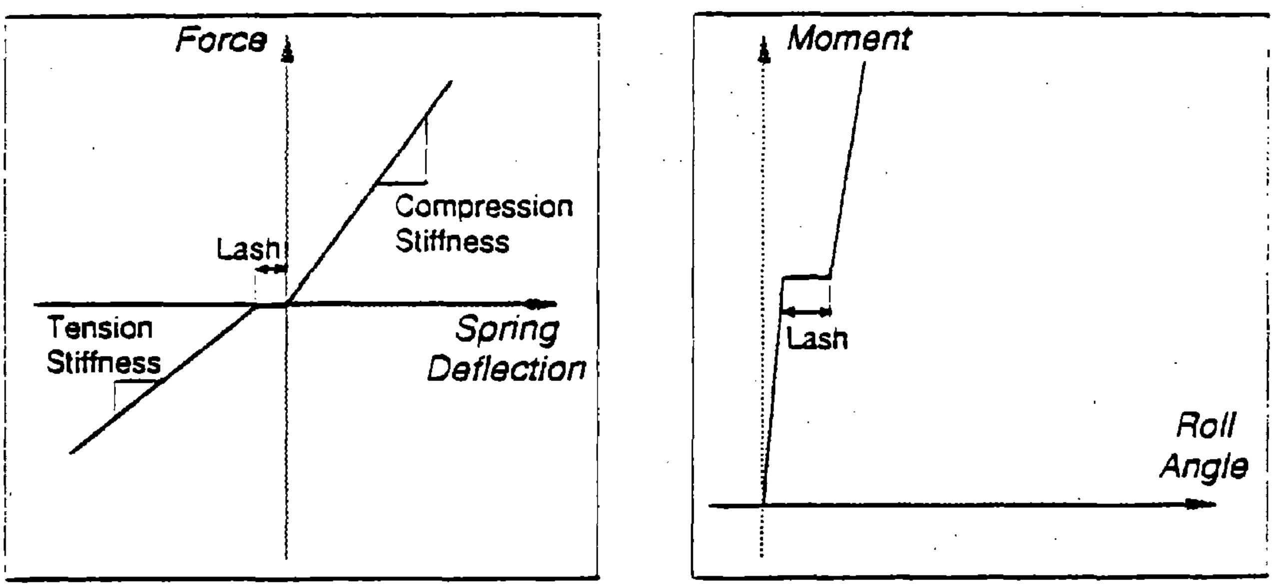


Figure 4. Roll response of a three-axle tractor-semitrailer.

However, at this point an additional parameter should be introduced to the process described above: lash. The parameter lash is attributed to the suspension, and when trailers and semitrailers are involved, it is also attributed to the fifth wheel hitch. The process described above encompasses springs and roll center "hinges" that are seemingly constant and fixed. In the case of the commonly used leaf springs, as the inbound spring gets unladen and extends until it reaches the zero load point, it does not exert a pulling force immediately. Instead, there is a no force travel of the spring when the leaf spring moves from resting against the spring slipper to rest against its retaining bolt. That phenomenon of inconsistent stiffness (K_s) is demonstrated in figure 5(a). A similar lash exists in the fifth wheel hitch. There is some clearance in the coupling mechanism between the king pin of the trailer and the fifth wheel hitch on the tractor (or the dolly). Under high levels of lateral acceleration, when the trailer transfers high levels of roll moment to the suspension of the tractor below, at a certain point the trailer starts to separate from the surface of the fifth wheel. As with the leaf spring, before the king pin can start exerting tension force on the plate, the trailer moves freely through the clearance gap. That "interruption" in roll moment transferal at the fifth wheel hitch is shown in figure 5(b).

By incorporating lash into the suspension, it causes the sprung mass to roll through a certain angle without any change in restoring moment. Then there is some additional increase in roll moment due to the tension slope of the spring [figure 5(a)], but it evolves only near the end of the travel. The inner wheel lifts off shortly after. As a result, the peak roll moment point shown in figure 3 drops, and the restoring moment capacity of a suspension with lash is therefore reduced. This phenomenon is demonstrated in figure 6, which displays a single suspension for clarity purposes.



(a) Suspension Spring **(b) Fifth Wheel Hitch**

Figure 5. Lash in suspension spring and fifth wheel hitch.

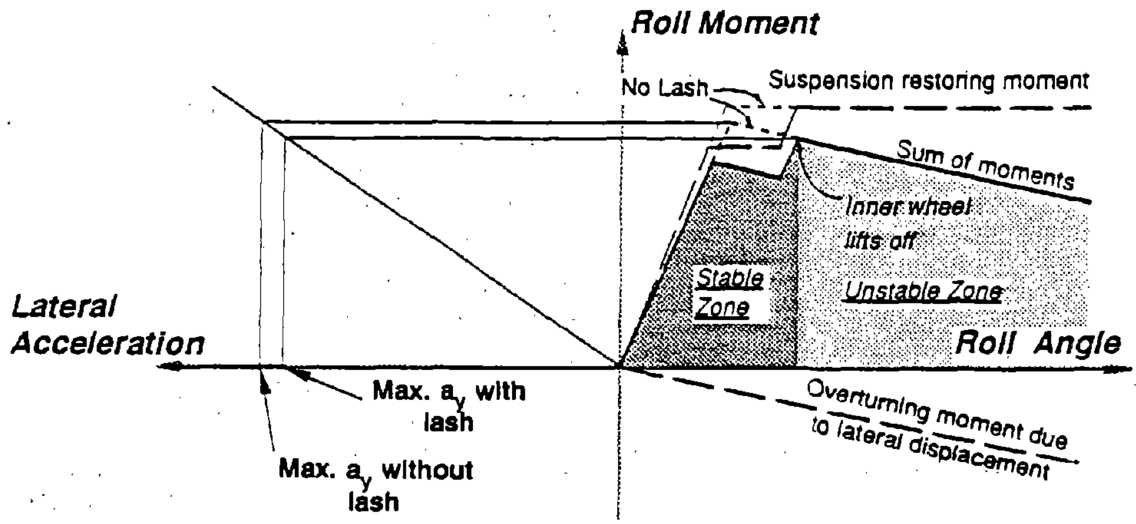


Figure 6. Roll response - single suspension with lash.

Fifth wheel lash assumes a similar role in reducing rollover threshold as the suspension lash. The "sum of moments" curve plotted in figure 4, or even such a line that incorporates the suspension lashes as demonstrated in figure 6, is based on a longitudinal rigidity of the vehicle. Such a rigidity is essential to enable the summation of the contribution of all the axles along the frame of the truck. With a fifth wheel lash there is an "interruption" of moment transferal as shown in figure 5(b). When a graph similar to figure 5 is drawn with the fifth wheel lash included, a "notch" (as the one in figure 5) will appear, causing the rollover threshold to be reduced. Figure 7 shows the sum of moments curve for the three-axle tractor-semitrailer with suspension and fifth wheel lash (without the individual suspensions).

Two more parameters affect the static roll stability of articulated trucks: compliance of the frame and articulation angle. The first one has an influence similar to the fifth wheel lash, since it interrupts the transfer of restoring moment from the various suspensions. Yet, its effect is somewhat more moderate since it acts as a smooth torsional spring without the sharp notches as in figure 7. Articulation angle simply reduces the contribution of the tractor's suspensions to the total restoring moment of the truck. It diminishes the tractor's moment in accordance with a cosine relationship: full contribution at zero articulation, and zero contribution at 90° articulation.

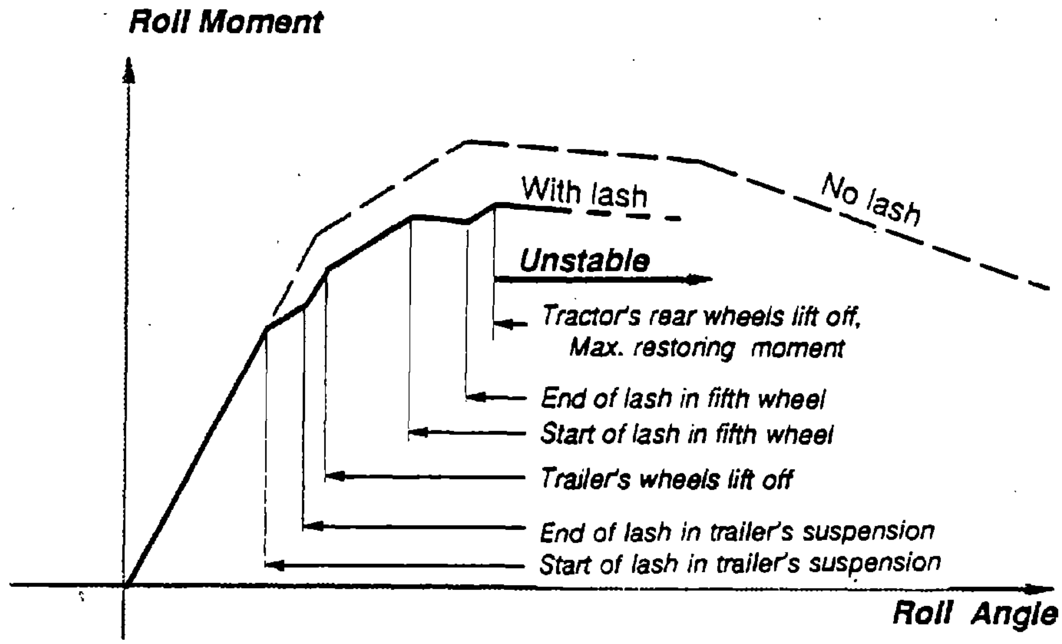


Figure 7. Restoring moment - three axles with lash.

Under dynamic conditions, the maximum level of lateral acceleration the truck can endure before rolling over drops even more. The static rolling process described above is a steady state, no-motion process, based solely on equilibrium of moments. "History" does not have any influence on the process. From the static point of view there is no difference if the truck is subjected to a given roll angle in a very gradual manner, or by a form of a step function. At a specific roll angle, the particular truck will have so many axles in the air and a given level of restoring moment (stable or unstable) – regardless of the process that brought it to that inclined state.

Dynamic evaluation of the rollover threshold involves transient effects of the maneuver. Since motion of masses suspended on springs and dampers are in question, quantities that were not accounted for in the static analysis can excite undamped modes of motion and amplify roll and yaw responses of the truck. Some of these quantities are inertia properties of the truck, roll rate of both the sprung and unsprung masses (rate of change in ϕ_1 and ϕ_2), lateral motion of the truck due to the lateral compliance of the tires (K_l in figure 3), articulation angle, and articulation rate. It is not just static response, but frequency response of the vehicle that can cause resonance and an accelerated rollover. The phenomenon of "rearward amplification" assumes a major role in evaluating dynamic roll stability during transient response. It results in an amplification of the roll and sway motions in articulated vehicles during maneuvers like "obstacle avoidance." For example, in a basic double trailer combination going through such a maneuver, an "input" lateral acceleration at the tractor of 0.17g (which, under static conditions, is still far from the rollover threshold) was amplified to 0.37g at the last trailer and caused rollover.[2,3] A comprehensive experimental and analytical investigation of that subject has been recently performed by UTMRI.

The effects of moving payloads and sloshing of liquids are even more difficult to evaluate, and they are usually taken into account by empirically adjusting the rollover threshold achieved analytically or experimentally (see next section). Tankers for instance, when loaded to 50 percent of the capacity, exhibit a slosh resonance frequency of about 0.3 to 0.5 Hz. Such frequency levels are common in the process of performing "obstacle avoidance" maneuvers. The influences of sloshing need to be taken into account when determining the rollover threshold for certain types of dynamic maneuvers.

ROLLOVER THRESHOLD DETERMINATION

The term "rollover threshold" was defined previously as the value of lateral acceleration beyond which (if the truck in question is subjected to it) an inherently unstable state prevails and the truck will roll over. It is specified naturally as a number in units of *g*. It should be emphasized that this value is not only specifically associated with a certain truck's configuration, but also with the loading conditions. As loading conditions vary, so does the rollover threshold.

Rollover threshold is usually determined by performing a test under static conditions -- a "tilt table" test. The schematic layout of the tilt table experiment is shown in figure 8. The vehicle is positioned on a tiltable platform (or a set of platforms -- one under each axle), and is subjected to a gradually increased roll angle. The roll rate of the tilt table is very slow to avoid dynamic effects. As the test progresses, axles start to lift off (the vehicle is secured to the table), until a point is reached when the vehicle goes unstable and keeps rolling with no increase in the angle of the tilt table. That point is registered as the rollover threshold with a simulated lateral acceleration that is the appropriate component of the earth's gravity (g).

If the dynamic process of rollover is to be addressed, the threshold can be determined by a full scale simulation, or a vehicle test that is much more complicated than the tilt table test.

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[2] A g is the acceleration due to gravity, which at sea level is 32.2 ft/s^2 (9.81 m/s^2).

[3] Reference 8, p. 19–61.

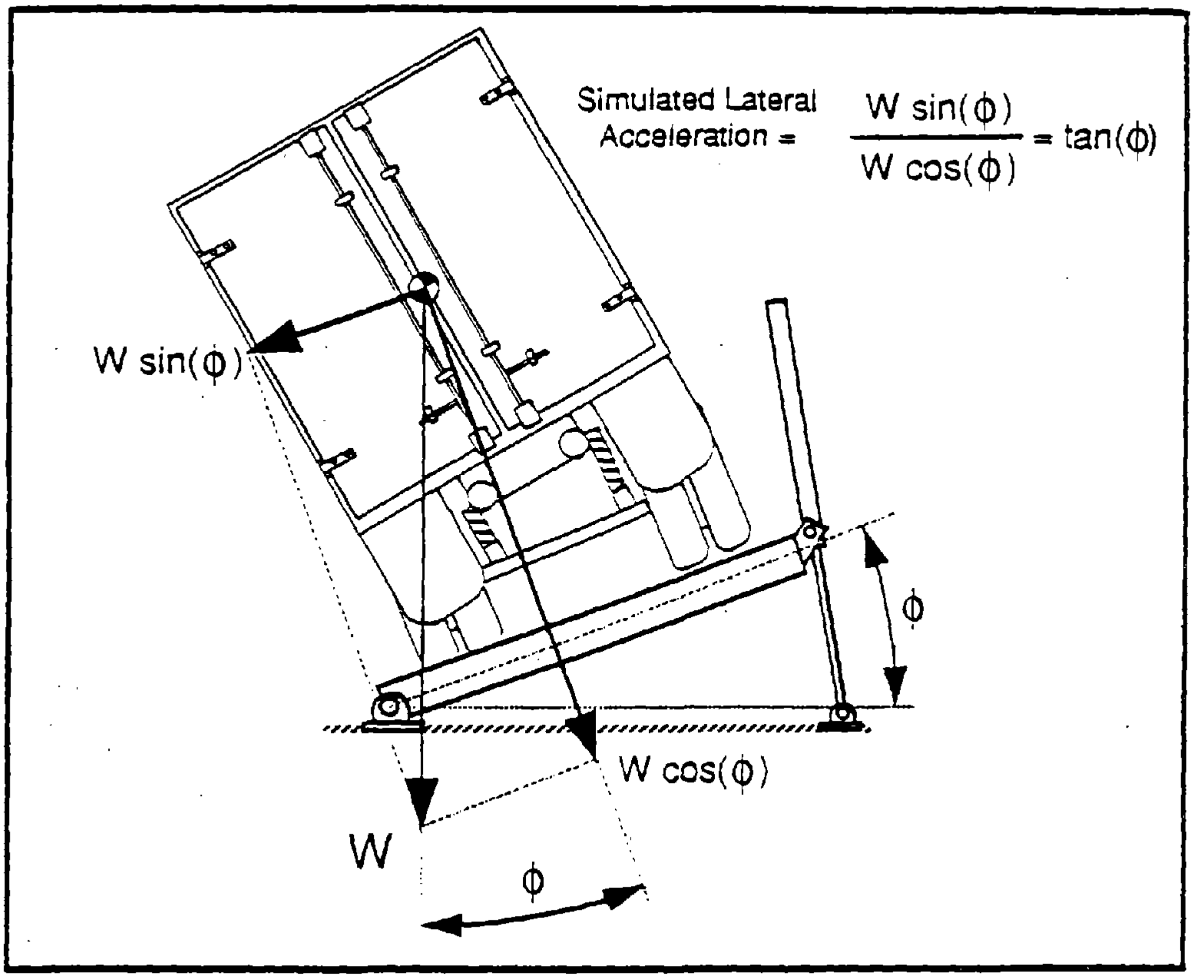


Figure 8. Tilt table experiment layout.

ROLLOVER ON HIGHWAY RAMPS

In the preceding sections, the rollover of heavy duty truck combinations was discussed without considering the environment in which they are driven. Going through a ramp, there is a variety of design parameters that can be identified as having an influence on the stability of the vehicle. Two of those are analytic by nature, and can be "quantified" into an equation to evaluate their contribution (or negation) to the roll stability of passing trucks:

- Superelevation of the ramp (e, in radians), which is the inclination of the road from the horizontal position (positive if into the turn, negative if outside).

- Radius of the ramp (r). It is usually not constant.

Additional design parameters that affect the stability are very complicated to be quantified, and their individual or combined influence can only be evaluated by means of tests on the ramps in question. As a design goal, their existence should be minimized. These additional parameters are listed below, but will not be discussed further:

- Jolting transition of superelevation along the ramp.
- Sudden change of curvature.
- Deceleration lanes that are either too short to sufficiently slow down, or are positioned on a downgrade.
- Curbs along the outside of the ramp that could trip the vehicle, thereby facilitating overturning.
- Reduced friction on the ramp.

For the purpose of demonstrating the interaction between truck and ramp properties that are pertinent to roll, figure 9 shows a simplified layout of the truck on the inclined ramp. For such a truck, traveling at a speed of V, the dynamic equilibrium of the lateral acceleration imposed on it in the vertical plane as in figure 10 can be expressed as:

$$a_y = \frac{V^2}{R \cdot g} - e \qquad (7)$$

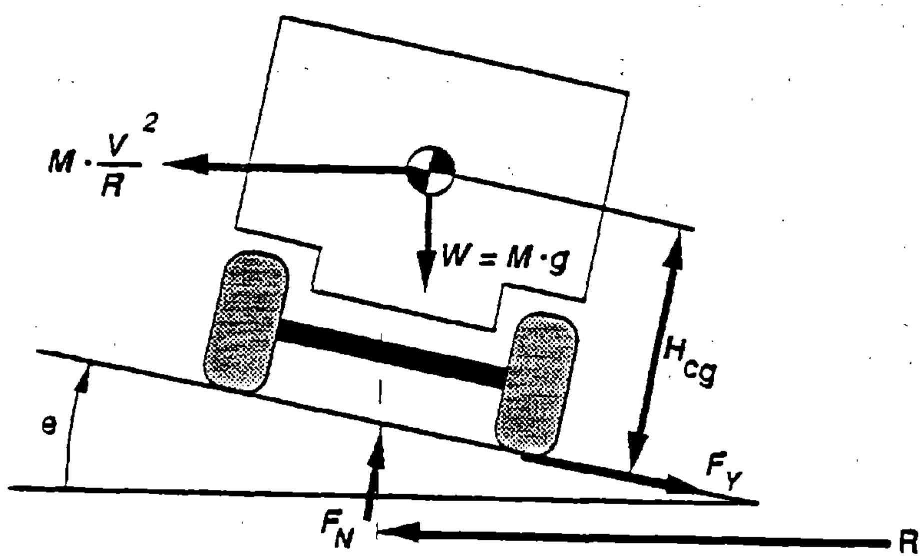


Figure 9. Forces and dimensions during superelevated turn.

Neither the curvature nor the superelevation can be expected to have constant values throughout the ramp. Moreover, one would expect to find the highest value of positive superelevation at the point where the largest level of curvature exists. This is hardly ever the case due to various design and construction constraints. As a result, the common ramp is characterized with an array of paired superelevation - curvature values. Each ramp has its own array. Since the superelevation and curvature are simultaneously used in the expression for the lateral acceleration (equation 7), it is necessary to determine which is the point along the ramp that is the most critical from the roll stability standpoint. To do that, the whole array of superelevation - curvature pairs of the ramp in question should be evaluated using equation 7, and the one that yielded the highest result is selected as the critical point.

Studies that were conducted by UMTRI were aimed towards establishing safe speeds of trucks on various highway ramps, and to determine the optimal way of displaying the warning. The ramps in the study were measured to find the relationship between speed and the subsequent lateral acceleration. That relationship was found to be of the form:

$$a_y = A \cdot V^2 - B \tag{8}$$

where A and B are empirical coefficients, attained by fitting the collected data.

In the course of driving through the ramp, steering fluctuations are introduced by the driver due to various reasons – from inconsistent ramp curvature to the control mechanism of an attempt to follow a path. When determining the safe and desired level of lateral acceleration, a safety margin should be considered, and an allowance should be made for the steering fluctuations. A 15-percent reduction factor is employed to count for the steering fluctuations.[15]

The expression for the safe lateral acceleration can therefore be written as:

$$a_{y_{max}} = \frac{RT - SM}{1.15} \tag{9}$$

where RT is the statically evaluated rollover threshold, SM is the designated safety margin, and 1.15 is the factor due to steering fluctuations.

CHAPTER 4. ALTERNATIVE WARNING SYSTEMS

FUNCTIONAL REQUIREMENTS

Given the principles and dynamics of truck rollover, an ideal automatic warning system would function as follows: A driver of a truck would be warned far enough upstream of a curved ramp to reduce speed to a level less than the threshold speed that would cause the truck to rollover, given its weight and center of gravity, on the curved ramp with a certain horizontal degree of curvature and superelevation. Given this general functional requirement, at least two detection/warning system concepts can be postulated.

In the first concept, a detector(s) placed in or along the road would identify the truck and its relevant parameters (speed, weight, etc.), and a warning device (i.e., a sign with or without some type of beacon) would be positioned prior to the curved ramp. A controller would receive the signal from the detector(s), process the information according to an algorithm that determines if the truck's speed may cause a rollover, and transmit a signal to activate the warning device should the truck speed be equal to or greater than the rollover threshold speed. This system will be identified as an inroad detection/warning system — an "intelligent highway" in the vernacular of the Intelligent Vehicle-Highway System (IVHS) program.

In the second concept, at the start of each trip the driver would enter information on the vehicle configuration (i.e., number of trailers, trailer type), cargo type and weight, load distribution, etc. Its speed would be continuously monitored from a sensor on the drive axle of the tractor and processed through the onboard computer. At each curved ramp (or those that have a history of rollover accidents or have a combination of degree of curvature and superelevation that has been found to be associated with truck rollover), there would be an electronic device (transponder) that would transmit the ramp geometrics data (i.e., ramp radius and superelevation). This radio signal would be received in a truck and processed in the onboard computer. A warning would be given to the driver, via an alarm signal or recorded message, to reduce speed if there is a possibility of rollover. This system will be labeled as an invehicle detection/warning system — an "intelligent vehicle," using the IVHS vernacular.

More details on how these two conceptual systems would operate, and what hardware and software would be necessary, are discussed in this chapter.

INROAD DETECTION/WARNING SYSTEM

The components of the inroad detection/warning system include the detector hardware, the controller for processing the electronic data, and the warning system. The requirements of these components are discussed below.

Detection System

For an inroad detection system to operate effectively it should be able to capture certain vehicle parameters, namely:

- Vehicle type – truck vs. non-truck.
- Speed and deceleration profile.
- Weight.

Ideally, it should also be able to detect the truck's center of gravity, but this is not possible for an inroad detection system. How this could be accomplished using various roadway detection systems is described below.

Vehicle Type Identification

Vehicle type identification would be one of the most basic and also essential functions of the system. In executing this function, the system would identify each vehicle that enters the ramp as belonging to one of two vehicle groups: trucks or non-trucks. This must be done as early as possible for each entering vehicle. The rest of the system would be activated upon positive identification of a truck. A truck is defined as any vehicle that belongs to vehicle classifications F5 through F13 of FHWA Classification Scheme F (see reference 17).

Trucks can be identified and classified by using either an inductive loop or a piezoelectric sensor or a combination of the two systems coupled with a controller to process the electrical charges. When trucks pass over these sensors imbedded in the pavement, they establish a vehicle charge or voltage profile that is matched with existing FHWA data base profiles to correctly classify vehicle type. There are several manufacturers of detection systems for classifying and measuring the speed of trucks. Therefore, any one of these commercially available systems can be used to establish a vehicle as being a truck or a non-truck. Although it is possible to identify each truck by its exact classification, there is no meaningful way in which this information can be used to improve the system.

One truck type classification that is important is distinguishing between a tanker trailer and a standard box trailer truck. Tanker trucks have a lower rollover threshold than box trailer trucks for the same weight. Since tanker trucks are typically lower than box trailer trucks, a vehicle height sensor can be used for detecting this type of truck.

Commercially available height detectors use a microwave-based radar beam as an "electric eye" to detect a vehicle within the beam angle. By adjusting the height of the detector above the pavement and properly angling the beam, this device can be used to detect trucks above or below a threshold height. Tanker trucks are typically 11 ft (3.4 m) or less, hence this height should be established as the threshold value.

Truck Speed Detection

The speed at which a truck is traveling at a specific point on a ramp is the most important variable as far as determining its rollover likelihood. Therefore, accurate and reliable truck speed detection should be a prime feature of this system. If the truck speed is detected too early, the assumptions regarding the truck's speed profile (based on truck deceleration rates) may not be accurate. On the other hand, if speed is detected too close to the curve, activation of a warning sign may not provide enough of a warning. Therefore, sensors for detecting truck speed should be placed such that this measurement provides a sound input for the sign activation logic.

The speed of a vehicle can be determined by using a pair of either embedded inductive loop detectors or piezo sensors. A controller is needed to process the electrical charges and determine the speed. Hence, the same detector hardware used for truck classification, when properly arranged, can be used to determine the speed of the truck.

Another desirable requirement of the system is to be able to determine the truck deceleration profile. Although a truck may be traveling faster than the calculated rollover threshold speed at a point upstream of the curved section, it may be decelerating at a rate such that it would be below the critical speed by the time it reaches the point of curvature. Speed deceleration profile can be determined by installing two-point speed detection systems.

Vehicle Weight Measurement

The weight of a truck can be used indirectly as a variable in determining the truck rollover threshold. Truck weights are obtainable by using commercially available weigh-in-motion (WIM) systems. These weighing systems use a combination of inductive loop and piezo sensors to provide electrical charges to a controller that is programmed to calculate the vehicle weight. WIM systems are available that can measure truck weight at an accuracy of 2 percent of the true weight for trucks traveling up to 70 mi/h (103 km/h).

Vehicle Detection By Video

A potential alternative to embedded inductive loops or piezoelectric sensors for detecting trucks is video imagery. This technology is steadily advancing and it is being used for some freeway surveillance systems. An assessment of its potential for this application is presented in appendix A. The findings of that assessment is that further development of video imagery is required before it can be used to detect the necessary truck characteristics with reliability.

Controller

An electronic controller is needed to accept the electrical inputs from the detection device, process the charges according to a prescribed logic for identifying a truck that is exceeding the rollover threshold, and send a signal to activate the warning device. The controller would be housed in a cabinet and be supplied electricity (110 volts) drawn from the nearest existing source. The capability of testing each of the components and the system as a whole would be built into the system. The maintenance personnel would have access to this feature through switches provided in the controller.

Presently, there is no "off-the-shelf" controller that can accept the input from the loop detectors, piezo sensors, and height detectors, process these electronic data according to the required logic, and activate the warning device. However, at least one manufacturer of a WIM system has indicated that its controller can be modified to do so.

Warning Device

There are at least two alternative devices that could be used to warn the driver. The first would be a static warning sign with yellow beacons that would flash when activated by the controller. The second would be a sign or message that would appear only when activated by the controller. The details of these two options are discussed below.

Figure 10 shows the suggested warning sign for the first option. It consists of a standard static truck rollover warning sign (similar to those already used), flashing yellow beacons, and a supplemental message explaining the flashing beacon. A recent FHWA study on evaluating driver preferences for alternative warning signs for trucks recommended three key features for a static warning sign.[18] These are:

- Rear Silhouette of a Tipping Truck.
- Diagrammatic Curve.
- Speed Advisory.

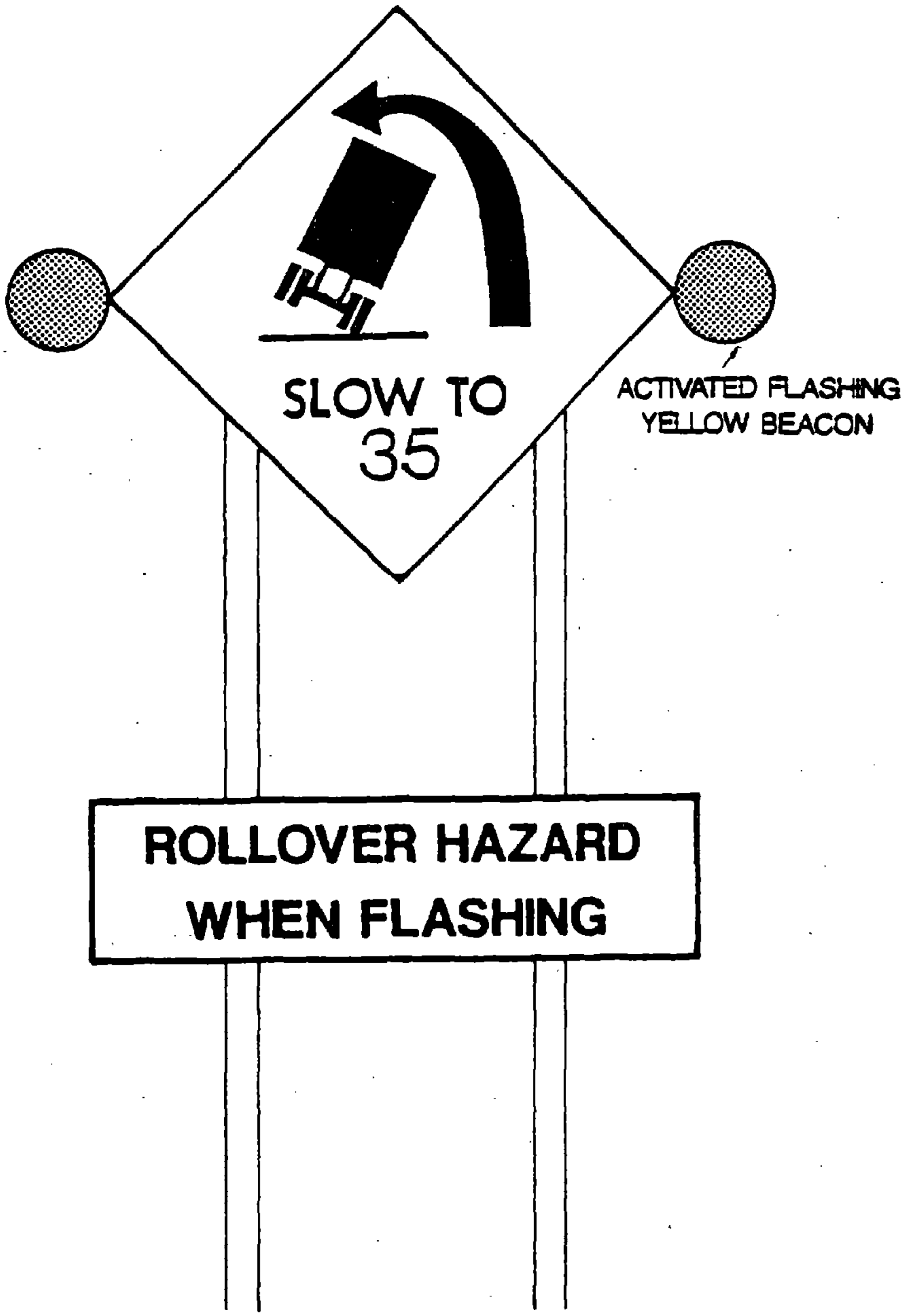


Figure 10. Warning sign option using flashing lights.

These features are incorporated into the static warning sign, which would be black on a yellow background. The speed value would be the same as the posted advisory speed already established for the ramp. The supplemental sign with the message ROLLOVER HAZARD WHEN FLASHING is necessary to emphasize the rollover warning. Its presence communicates to the truck drivers that there is a system that will warn them if they are going too fast. Alternative messages for this supplemental sign would be:

- ROLLOVER POSSIBLE WHEN FLASHING.
- REDUCE SPEED WHEN FLASHING.

The second option for a warning system is shown in figure 11. It would consist of the static truck rollover warning sign (without the flashing beacons) and a supplemental sign with the message TRUCKS REDUCE SPEED, which would appear only if a truck is at or exceeding the rollover threshold speed. A fiber optic sign would be used to achieve this requirement.

For either option, the warning device would be activated when the system logic in the controller has determined the presence of a truck with a high rollover potential. The warning device would be deactivated after it has been active for a fixed duration. This duration should not be less than the time taken by the truck to travel past the point of curve (PC) or point of tangent (PT) of the curve in question, or any other ramp curve of equal or smaller radius. The reasoning behind this provision is that such timing would enable multiple warning signs to be controlled via the same controller. This would be particularly useful on loop ramps where two sharp curves are separated by a curve with a larger radius. If the second curve has the smaller radius, the system logic should be based on this radius.

Sign Location

Since the objective of the system is to provide a warning to the driver, the sign must be located at a point such that there is adequate distance and time (speed dependent) to the PC of the first curve. This distance would be determined by taking the following into consideration:

- The sign should be clearly visible and legible to a truck driver from a certain point P on its path towards the ramp.

- The distance from point P to the PC or the start of the ramp curve should be sufficient to allow the driver of a truck driven at speed V_a to see and react to the warning sign, apply brakes, and reduce its speed down to a safe speed, V_s, prior to entering the curve.

This may result in some ramps geometrics not having the physical features necessary to meet these requirements. When evaluating the feasibility of installing a warning system on a candidate ramp, this would be an essential qualifying criterion.

The preferred location for the warning sign is on the inside of the curve approach. However, at ramps where it is not possible to locate as such, the sign may be placed on the outside as long as it is sufficiently protected from errant vehicles.

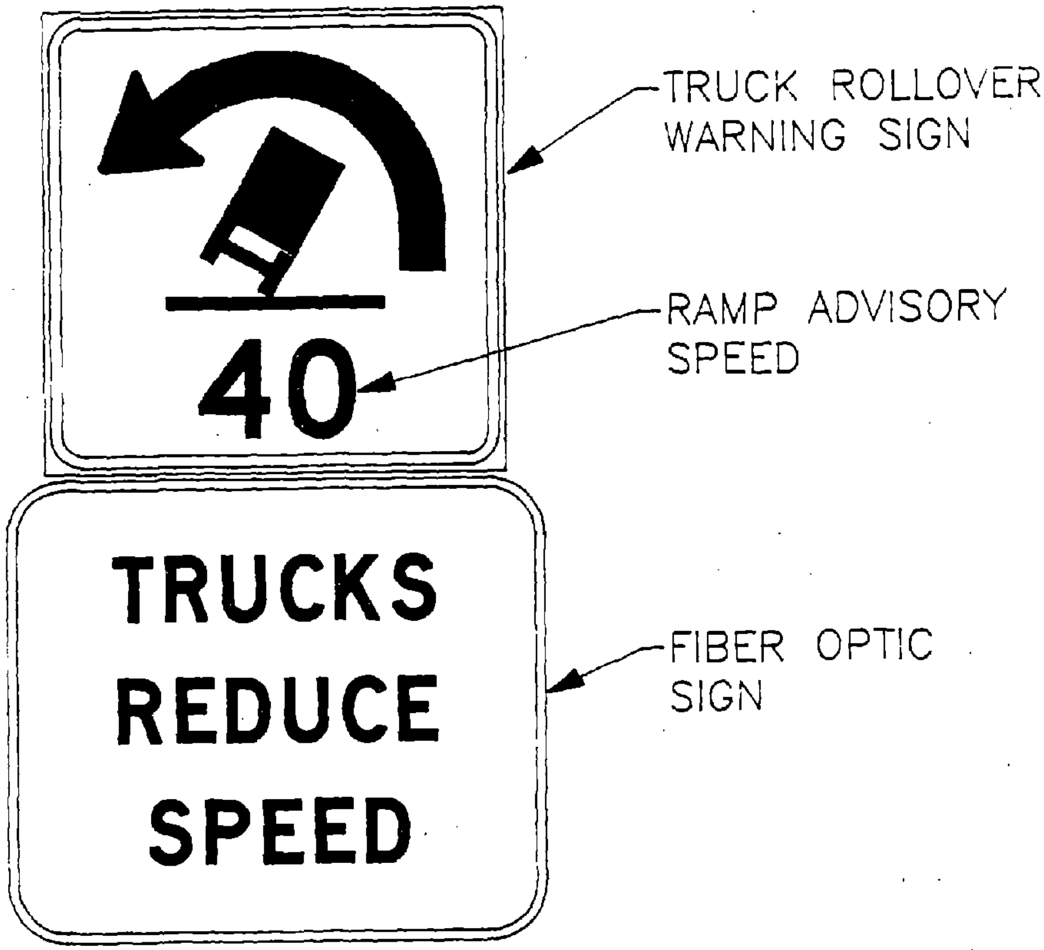


Figure 11. Warning sign option using fiber-optic sign.

ALTERNATIVE SYSTEM CONFIGURATIONS

Given the generalized functional requirements presented, two inroad system configurations are possible. They are identified as system A and system B.

System A

System A would use only two vehicle variables – truck classification and speed. It is the least complex warning system proposed. However, this system would meet the minimum functional requirements desired for meeting the objectives of a warning system. The number of inputs required for determination of rollover likelihood or sign activation is kept at a minimum in this system. This results in some trade-off in the accuracy of detecting a rollover likelihood. The logic that controls sign activation is designed to err on the side of safety. That is, the warning system would be activated more frequently than it would be if it had perfect information. As a result, some false alarms are to be expected when the warning sign is activated for trucks identified as having a high rollover potential.

This system will use a programmable traffic classifier controller. The classifier receives signals from inroad sensors, interprets them, and passes them on to a recorder, which performs the basic calculations for speed and vehicle classification. A commercially available controller has been identified as a suitable programmable classifier. The proposed system will need additional software and hardware related to the development of a transistor-transistor logic (TTL) output board to required specifications. The TTL output board will allow for pre-selected truck speeds and types to be represented as a 5-volt signal to activate the logic circuitry controlling the warning device. Two permanent piezoelectric sensors and one permanent loop sensor will be used to input speed and vehicle classification data into the system for processing. The processing software will be used to program the unit for vehicle classification.

Sign Activation Logic

A typical ramp installation for this system is shown in figure 12. For this system, the warning device would be activated based on the logic described as follows. For a particular ramp that has a minimum radius (**R**) for one of its curves, with a superelevation (**e**), the speed threshold ($\mathbf{V_t}$) for a truck is determined assuming the following:

- Since the weight of the truck is not detected, it is assumed to be a fully loaded trailer truck. The rollover threshold for this truck is assumed to be 0.24g.
- A safety margin of 0.10g is assumed.
- Typical deceleration ability of a truck is assumed to be linearly varying from 0.18g at 30 mi/h (44 km/h) to 0.28g at 70 mi/h (103 km/h).

- The perception-reaction time of the truck driver is assumed to be 2.5 seconds.

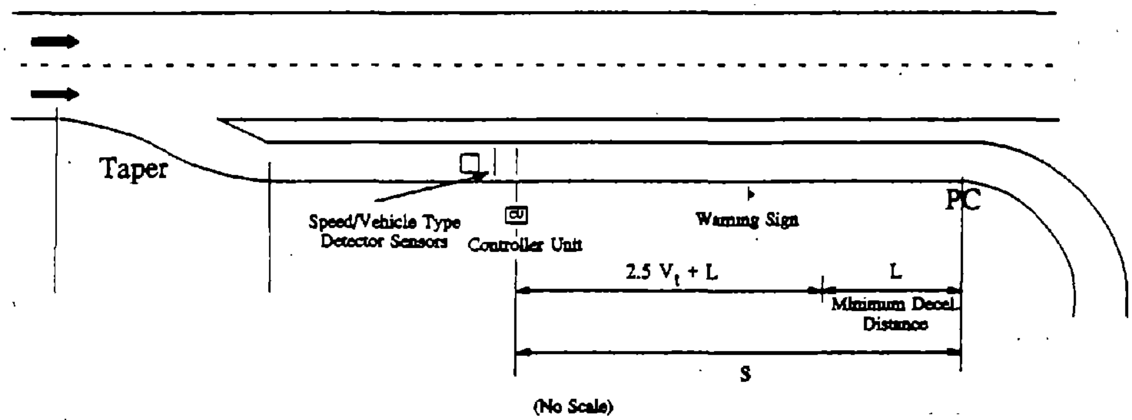


Figure 12. Typical ramp installation for system A.

The speed of a truck is detected at a distance **S** (>L) from the PC of the curve through a sensor in the pavement. If this speed exceeds V_t, then the sign will be activated. Most truck drivers upon seeing the sign warning system from a point on the ramp located at a distance (L + 2.5 V_t) from the PC will be able to decelerate over a distance **L** and enter the curve at a safe speed. (It must be emphasized that the system will not be able to provide sufficient warning to trucks driven at all speeds due to obvious limitations.) The distance **L** is based on the maximum speed at which the truck can enter the ramp curve without exceeding the rollover threshold.

To calculate the minimum deceleration distance required, the following calculations are performed:

- From equation 9, as shown below:

$$a_{y_{max}} = \frac{RT - SM}{1.15}$$

$$a_{y_{max}} = \frac{0.24g - 0.10g}{1.15}$$

$$a_{y_{max}} = 0.1826$$

- Equating $a_{y_{max}} = (V_{max}^2/R)\,(g \bullet e)$, assuming e equals 0.08 and solving V_{max},

  $$V_{max} = \sqrt{6.496 \cdot R}$$

  where R = radius of curve.

- Minimum deceleration required to slow down to V_{max} can then be calculated as follows:

  $$L = \frac{V_e^2 - V_{max}^2}{2 \bullet d}$$

  where V_e is speed of the truck at the ramp entrance (detection speed), d is the AASHTO braking deceleration for trucks from 0.18g to 0.28g for speeds ranging from 30 mi/h (44 km/h) to 70 mi/h (103 km/h).

A graphical plot of the minimum deceleration distance required and detection speed for radii between 1,000 ft (122 m) and 800 ft (244 m) is shown in figure 13.

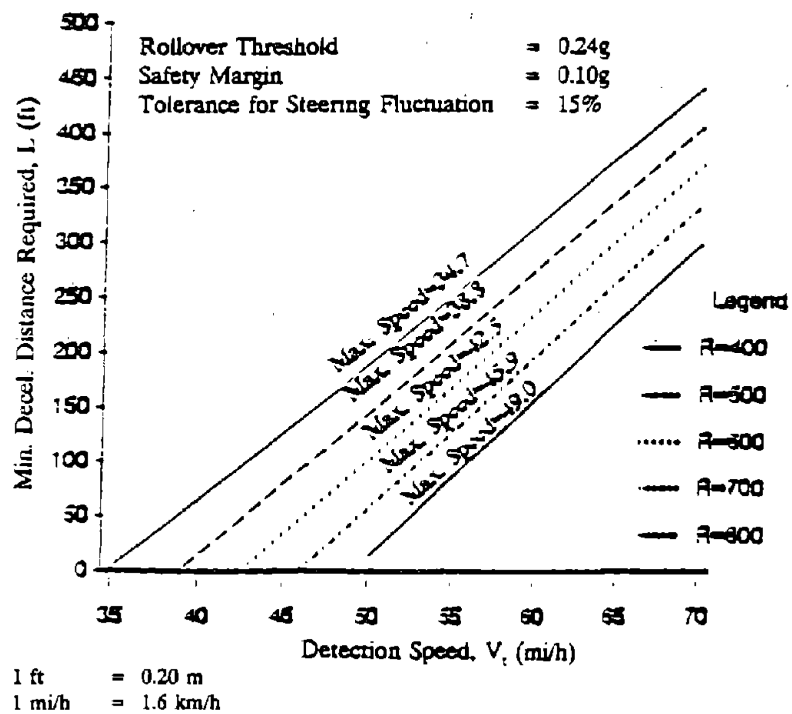


Figure 13. Relationship between minimum deceleration distance required and detection speed for different radii.

The operational logic of system A as defined here is depicted in figure 14.

System B

This system will use a piezoelectric programmable classifier controller. The classifier collects/retrieves signals from sensors embedded in the pavement, interprets them, and passes them on to a recorder, which converts these signals into speed, weight, height, and vehicle classification. These signals are then used to determine a TTL level to activate the sign. This is accomplished by the system logic that is preprogrammed for the specific ramp features. For this purpose, a commercially available piezoelectric programmable classifier has been identified. An additional TTL output board will be necessary for this system. The TTL output board will allow for pre-selected truck speeds and types to be represented as a 5-volt signal to activate the logic circuitry controlling the warning device. Two permanent piezoelectric sensors and one permanent loop sensor will be part of this system. These will detect and transmit speed, weight, and vehicle classification data into the controller. A narrow beam radar detector will be used as a sensor to detect a vehicle height threshold. Figure 15 shows a general layout installation for this system.

Sign Activation Logic

The logic that activates the sign in system B is driven by four inputs. This is an improvement upon the first system, which uses only two inputs – truck identification and speed. The additional inputs are truck weight and truck height. The sign activation logic in this system is similar to that of system A, except that less of an assumption is made regarding truck weight or loading. Input on truck height will be used to identify box trailer trucks and tanker trucks.

The relationship between truck gross weight and its rollover threshold will be used to determine the appropriate rollover threshold. Table 4 shows the rollover thresholds for example vehicles. Based on these results, a fully loaded truck with gross weight equal to or exceeding 80,000 lb (36,320 kg) has a rollover threshold of 0.24g (assumed for system A). For trucks carrying less than truck load (LTL) freight, the rollover threshold is slightly higher at 0.28g. By defining different truck weight levels it is possible to estimate rollover thresholds for various loading levels. It has been noted that the dynamic loads due to vibrations of the vehicle might have a root mean square (RMS) amplitude of 10 to 30 percent of the static loads. Due to this reason, the weigh-in-motion (WIM) measurement may need to be adjusted or calibrated. Figure 16 shows a basis for selecting the rollover thresholds for various loading conditions. This figure also indicates the frequency at which trucks with different loading conditions are involved in rollover accidents.

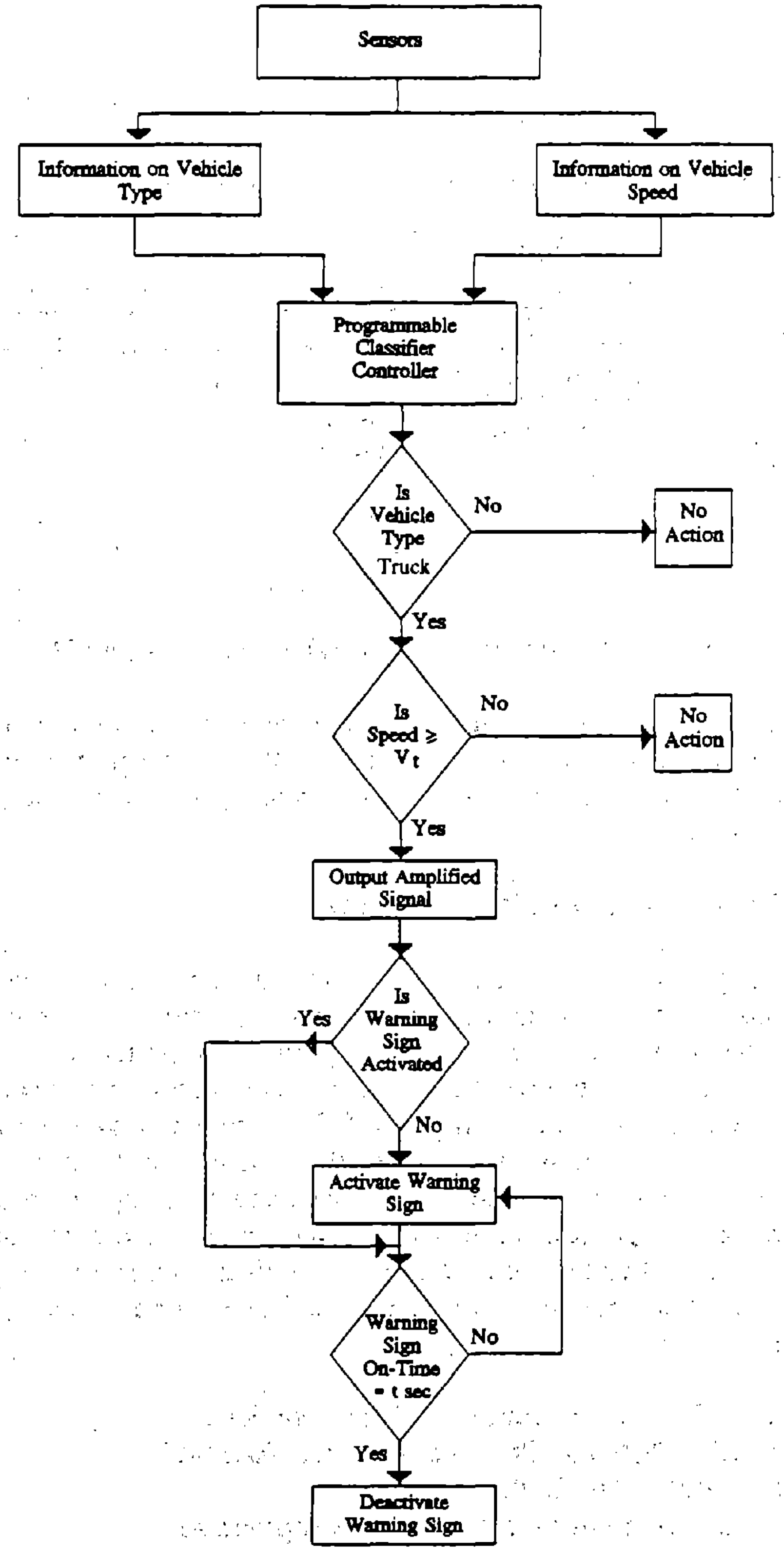


Figure 14. Operational logic of system A.

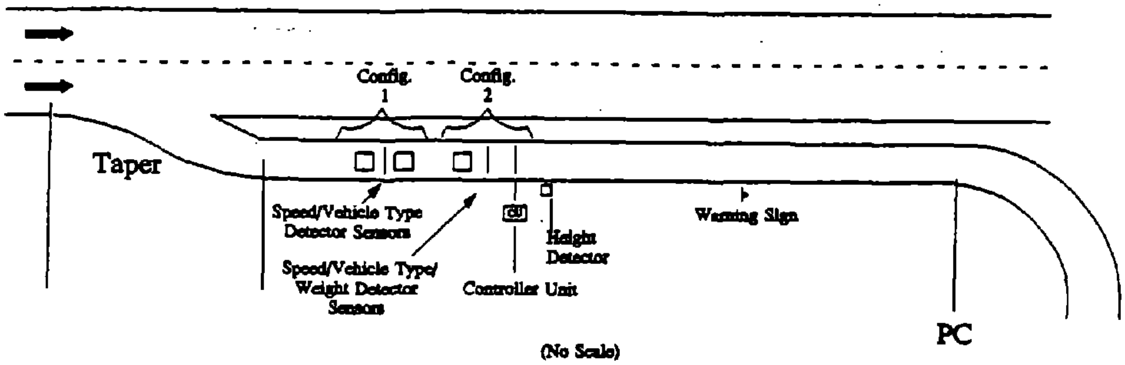


Figure 15. Typical ramp installation for system B.

The remainder of the sign activation logic is very similar to that described for system A. The speed threshold V_t is based on the rollover threshold for a particular truck. If the truck speed exceeds this speed threshold, the sign will be activated. Figure 17 shows the operational logic of system B.

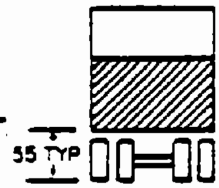
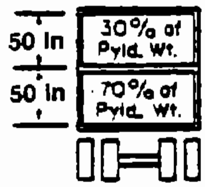
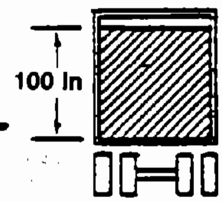
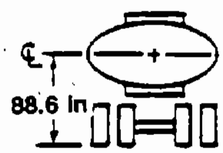
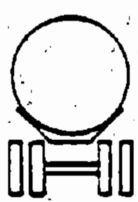
INVEHICLE DETECTION/WARNING SYSTEM

This system is based on equipment located both at roadside and in the vehicle. The components of this system use semi-active microwave technology and consist of four basic components: an invehicle electronics reader, antenna, transponder (type 3), and an onboard computer. The transponder transmits its identification data (ramp radius R, superelevation e, and distance L from truck to PC) to the antenna when a sensor detects a truck at distance L. The antenna then relays this information to the reader, where it is sent to the onboard computer for processing. The onboard computer processes transponder data (R, e), operator input data (vehicle, cargo, load types, and vehicle height), and vehicle speed and weight data, it then activates an invehicle warning device if rollover is likely. To carry out these functions, the following have been identified as suitable components:

- Vapor Roadcheck (reader and transponder).
- Amtech's PCB Log-Periodic Antenna (AA3140).
- RF module (AR2200).
- Onboard computer (Intel 8086) microprocessor.

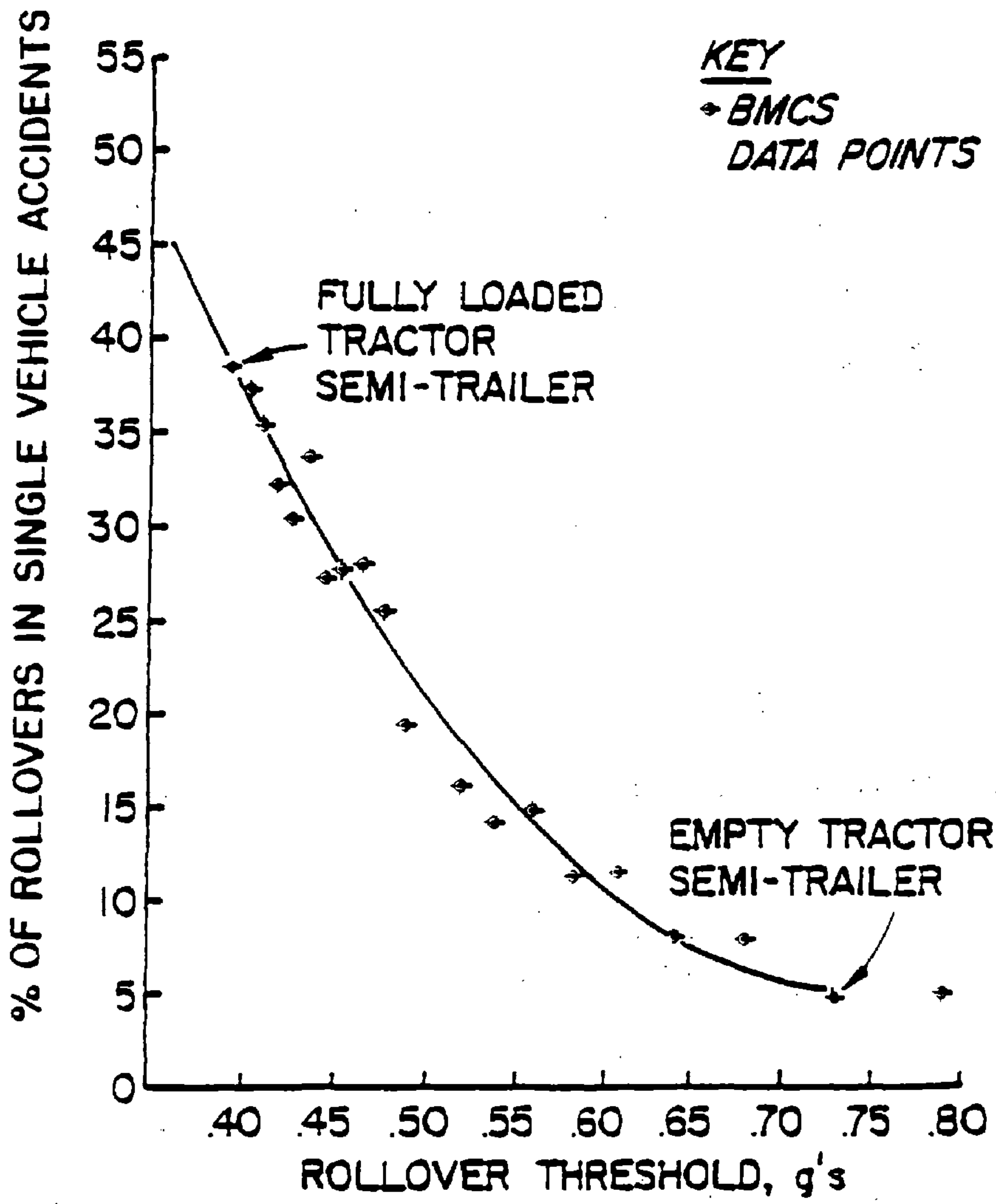
Figure 18 shows a schematic of system C.

Table 4. Rollover thresholds for example vehicles and loading conditions.

	CASE		CONFIGURATION	WEIGHT (lb) GVW	PAYLOAD CG HEIGHT (in)	ROLLOVER THRESHOLD (g's)
"BASELINE"	A.		Full Gross, Medium-Density Freight (34 lb/ft^3)	80,000	83.5	.34
	B.		"Typical" LTL Freight Load	73,000	95.0	.28
"HIGH-CG"	C.		Full Gross, Full Cube, Homogeneous Freight (18.7 lb/ft^3)	80,000	105.0	.24
	D.		Full Gross Gasoline Tanker	80,000	88.6	.32
	E.		Cryogenic Tanker (He_2 and H_2)	80,000	100.0	.26

1 lb = .454 kg
1 in = .0254 m
1 lb/ft^3 = 16.01 kg/m^3

Source: *Impact of Specific Geometric Features on Truck Operation and Safety at Interchanges*, UMTRI, August 1985.



Source: "Unintended Responses of Heavy Trucks to Braking or Steering Inputs," *HSRI Research Review*, March-April 1980.

Figure 16. Relationship between loading, rollover threshold, and percentage of rollovers.

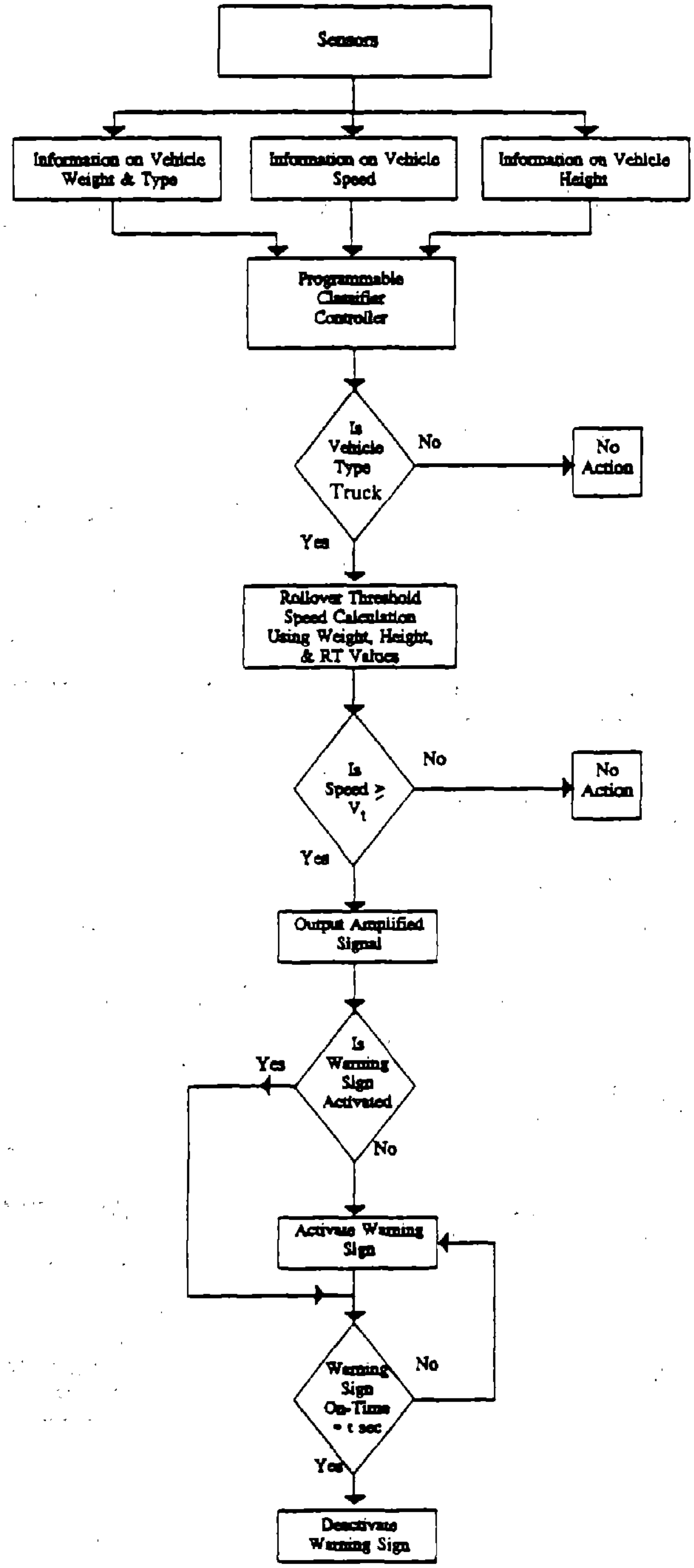
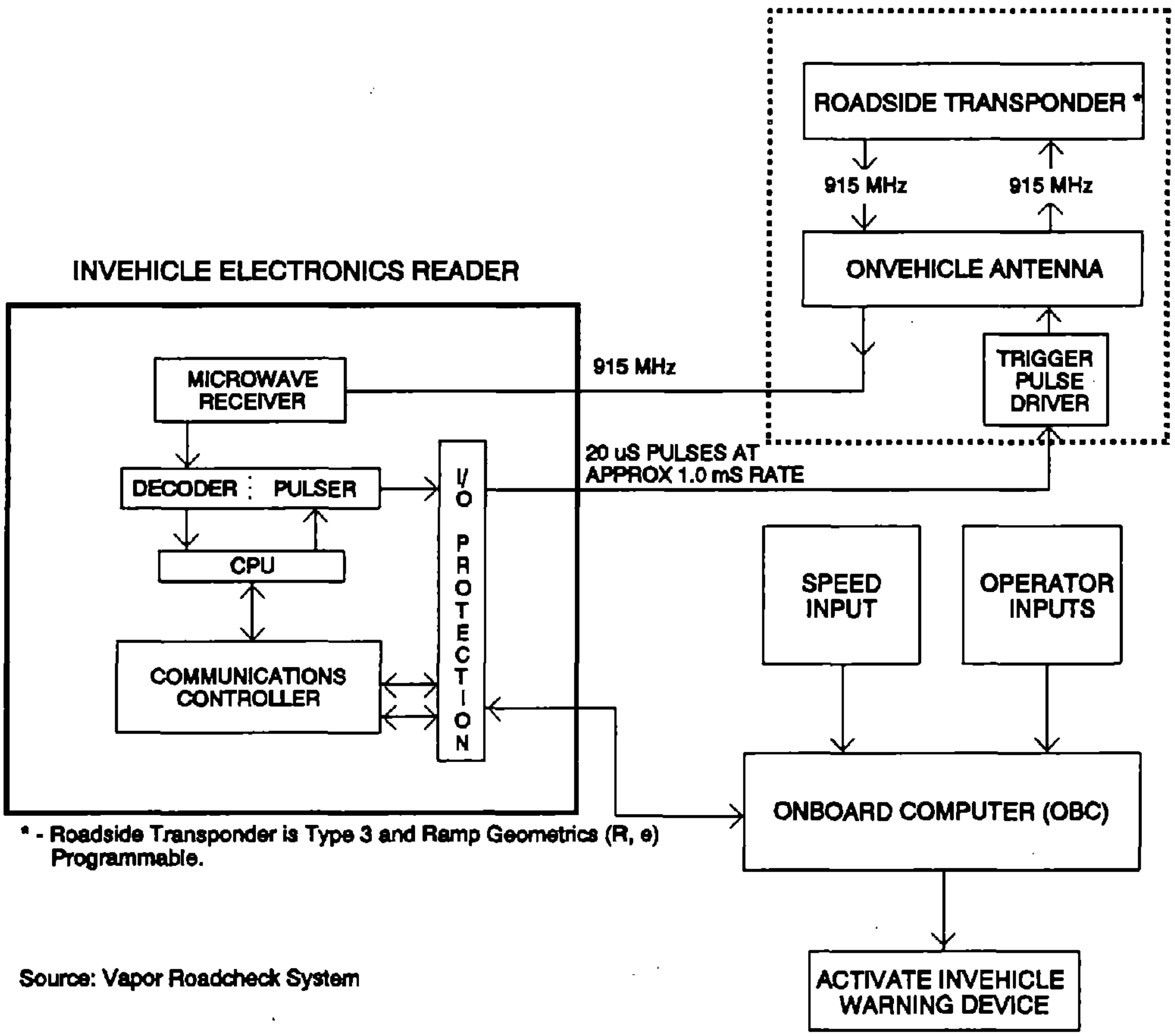


Figure 17. Operational logic of system B.

SYSTEM C - CIRCUIT BLOCK DIAGRAM



* - Roadside Transponder is Type 3 and Ramp Geometrics (R, e) Programmable.

Source: Vapor Roadcheck System

Figure 18. Schematic of system C.

Sign Activation Logic

The sign activation logic in system C would be of the highest precision of all three systems. The principal reason for this is that the rollover threshold of each truck is determined with fewer assumptions.

The operational logic of system C is shown in figure 19.

BENEFITS AND LIMITATIONS

The following is a discussion of the benefits and limitations of each of the proposed systems.

System A

Benefits of this system are that it would be relatively inexpensive to build, install, operate, and maintain. Therefore, if the system proves to be effective in alerting a truck driver of possible rollover, it may be installed at other such locations. The system requires three sensors on the road similar to that for system B. One advantage of initially installing system A is the feasibility of upgrading to system B in the future, in order to increase accuracy of detection. Since the classifier used to detect speed can also be used to collect data on passing trucks, it would be possible to monitor the performance of the system easily.

A limitation of this system is that due to the generalizing assumptions in the system logic (such as truck loading), the rate of false alarms may be the highest of all three systems. However, during fieldtesting it would be possible to fine-tune or calibrate the threshold speed setting to a realistic value.

System B

This system will account for the fact that empty trucks have a higher rollover threshold than loaded trucks. Another feature that increases its accuracy over system A is its height-sensing device. Information on vehicle height will be useful in determining whether the truck is a full van truck or a flatbed, or a tractor without a trailer. Although these types of vehicles are infrequent, the cost involved for additional information is well worth the achievable reduction in false alarms. This system also has the ability to store data while the system is in operation, thus providing a means of collecting valuable data on its performance as well as vehicle speed and volume data at these locations. This

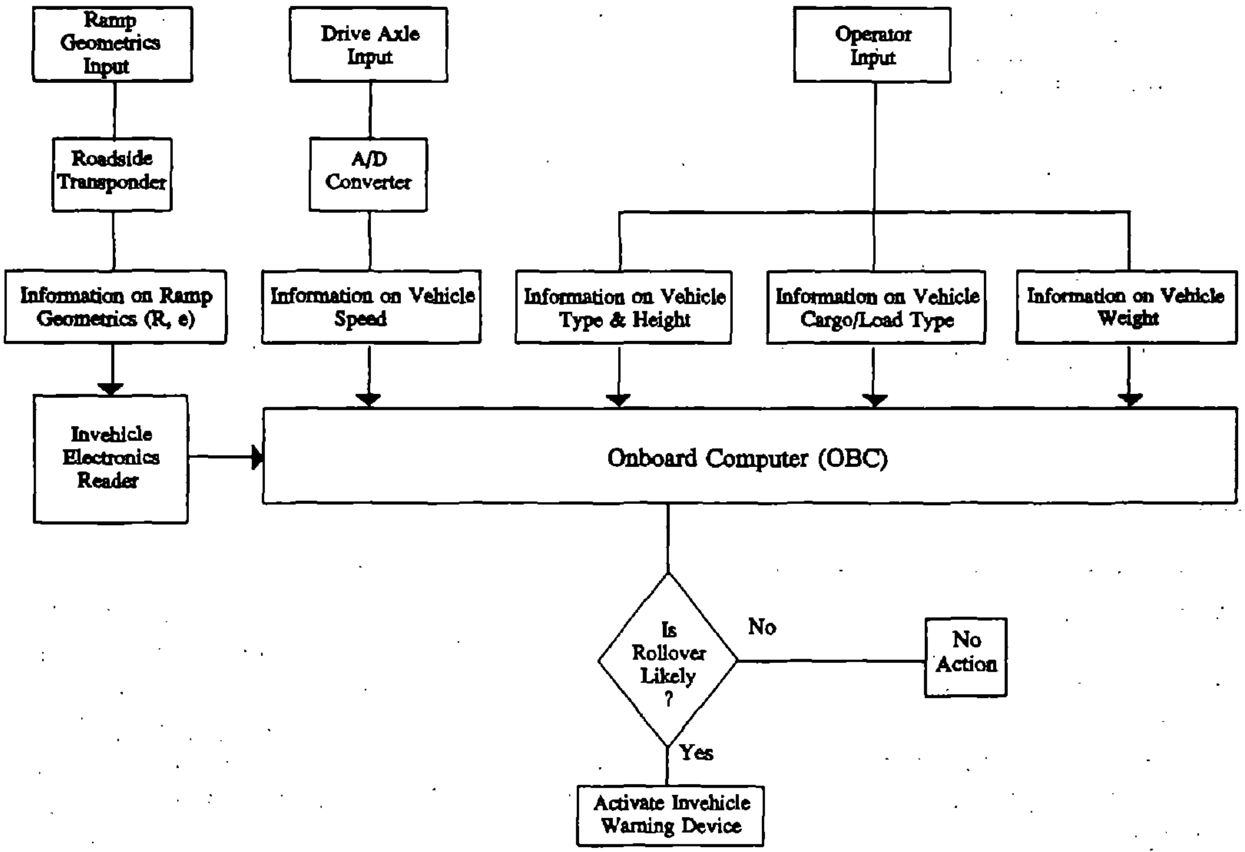


Figure 19. Operational logic of system C.

system is relatively inexpensive when compared to the savings that can accrue by preventing rollover accidents on busy freeways.

The limitations of this system are that in estimating the vehicle rollover threshold based on truck weight, assumptions made about cargo density may lead to false alarms for certain trucks. For example, a truck carrying a high density cargo with a low center of mass would be identified as having a lower rollover threshold typical for a truck carrying full gross, full cube, homogeneous cargo.

System C

The main advantage of an invehicle system is that its accuracy in predicting rollover possibility is higher than the other two systems. Information on vehicle type, its dimensions, characteristics of cargo, etc. will enable this system to minimize false alarms. Since the only components required on the ramp are the transponder and the loop detector, the cost of installing the system at ramps is low. However, for the system to function effectively, all trucks must have the onboard system installed. This creates some doubt about the implementability of this system based on current costs and technology. Although this system has a high initial cost at present, it may become a feasible solution for this problem in the future.

COSTS FOR INSTALLATION, MAINTENANCE, AND OPERATION OF ALTERNATIVE WARNING SYSTEMS

Hardware and Software Development Costs

A preliminary estimate of the hardware and software development costs for each of the proposed systems are discussed below.

System A: Description of Costs

The total cost of system A is made up of the costs of equipment, development, installation, training, operation, and maintenance. Cost of equipment/components includes a programmable traffic classifier, Post Processing Software-2, loop and piezoelectric sensors, a cabinet, sign and flashing beacons, conduit, junction boxes, and other discrete components. Cost of development includes hardware and software development of the classifier. Cost of installation includes installation of all equipment and components mentioned above. Cost of operator training includes manufacturer training on the controller. Cost of operation and maintenance includes electrical power cost, scheduled and unscheduled replacement of components such as beacons on the sign, pavement embedded loop sensors, and other components of the controller. These costs are itemized below:

System A Total Costs

Hardware/Component Costs	$8,000
Developmental Costs	12,000
Design Costs	5,000
Installation Costs	21,000
Operators Training Costs	1,000
Total Installation Costs	$47,000
Annual Operation/Maintenance Cost	$ 2,500

System B: Description of Costs

The total cost of system B is made up of costs of equipment, development, installation, training, operation, and maintenance. Cost of equipment and components includes a programmable classifier, a tracker Narrow Beam Radar Height Sensor, loop and piezoelectric sensors, a cabinet, cable, flashing beacons and signs, conduit and junction boxes, and discrete components. Cost of installation includes installation of all equipment and components mentioned above. Cost of operator training includes manufacturer training on the controller. Cost of operations and maintenance includes electrical power cost to system, loop and piezoelectric sensor replacement, and lamp replacement. These costs are itemized below:

System B Total Costs

Hardware/Component Costs	$20,000
Developmental Costs	20,000
Design Costs	7,000
Installation Items Costs	30,000
Operators Training Costs	1,000
Total Installation Costs	$78,000
Annual Operation/Maintenance Cost	$ 3,000

System C: Description of Costs

The total cost of system C is made up of costs of equipment/components, development, design, installation, operator training, operation, and maintenance. Cost of equipment includes the Vapor Roadcheck System (reader and transponder), Amtech PCB Log-Periodic Antenna (AA3140), and RF module (AR2200) and onboard computer (8086 microprocessor integrated circuit). Cost of development includes hardware and software development of the Roadcheck Reader and onboard computer. Cost of design includes the design of modifications. Cost of installation includes installation of all equipment mentioned above. Cost of operator training includes training on the onboard computer. Cost of operations and maintenance includes normal maintenance costs involving replacement of hardware such as the user input key pad and axle speed sensor.

System C costs are divided into C.1 vehicle-based and C.2 roadside-based hardware costs and are listed below:

Type of Cost	Vehicle-Based Equipment (C.1)	Roadside-Based Equipment (C.2)	Total Cost
Hardware Costs	$ 20,000	$ 100	$ 20,100
Developmental Costs	47,000	3,000	50,000
Design Costs	24,500	500	25,000
Installation Costs	5,000	1,000	6,000
Operators Training Costs	1,000	200	1,200
Annual Operation/Maintenance Costs	1,500	100	1,600
Total Cost	**$ 99,000**	**$ 4,900**	**$ 103,900**

SELECTION OF AN ALTERNATIVE FOR FURTHER CONSIDERATION

This section presents a trade-off analysis among the candidate systems proposed based on a number of factors that reflect desirable qualities in such warning systems.

Trade-Off Analysis for Candidate Systems

This involves a comparison of costs and benefits associated with each system considering factors such as: estimated cost, percentage accuracy of identifying rollovers (100 minus percentage of false alarms), adaptability to all ramps, and availability of system components. Some of these factors can be estimated with a high accuracy and others can only be estimated subjectively. For example, the cost of systems has been estimated fairly accurately. However, it is a rather complex task to determine the frequency of false alarms without knowing how often the assumptions made in the system logic is violated. The frequency of such violations depends on the distributions of vehicle and driver characteristics about the mean values assumed. This may also be site-dependent, such as ramps located near a steel mill would have trucks hauling high-density, low center-of-mass freight. Therefore, in attempting to carry out this trade-off analysis, subjective ratings were used for frequency of false alarms, adaptability to all ramps, and availability of components.

The cost of each system was estimated assuming a 20-year design life. The total costs reflect both initial and annual costs expressed in terms of 1992 dollars. Values for accuracy of identifying rollover, frequency of false alarms, adaptability to all ramps, and the availability of components were assigned based on factual information reported elsewhere in this report and the level of expected performance of each system.

Table 5 shows the summary of this trade-off analysis.

Table 5. Trade-off analysis of candidate system.

Alternative	Estimated Cost * ($)	Accuracy of Identifying Rollover	Frequency of False Alarms	Adaptability to All Ramps	Availability of Components
A	70.526	Moderate	Moderate	Moderate	High
B	105.075	High	Low	Moderate	High
C**	118.009	Very High	Low	High	Low

* Based on 20-year life for system.
** Per single ramp and single vehicle.

Very High High Moderate Low

Selection of Most Cost-Effective System

It is not realistic to assume that system C will be considered as a candidate system at the present time. The reason is the high-cost component to be borne by the trucking industry for the invehicle system. This leaves system A and B as the only viable options. Of these two, the most cost-effective system will be selected, taking into consideration information shown in table 5 and other factors, such as the location where the system is likely to be installed, and availability of funds for installing the system. Considering the benefits and limitations of systems A and B in general, system B appears to be the most cost-effective warning system. It is also possible to install a system B controller to perform as system A initially, to be upgraded to system B at a later date by the addition of the height sensor.

CHAPTER 5. DESIGN AND COSTS FOR SELECTED SYSTEM

Of the three optional detection/warning systems discussed in the previous chapter, system B was selected for further design development. Also, in consultation with representatives of the Virginia and Maryland Departments of Transportation, three ramps were selected for preparation design plans and eventual installation and evaluation. These ramps were:

- Ramp from I-495 North (inner loop of Beltway) to I-95 North in Maryland.
- Ramp from I-95 South (inner loop of Beltway) continuation of I-95 South in Virginia.
- Ramp from I-495 North (inner loop of Beltway) to VA Rte. 123 in Virginia.

The first and second sites are dual-lane exit ramps, a condition that imposed additional design considerations.

DESIGN CONFIGURATION

The selected system will consist of three in-pavement detector systems and a vehicle height sensor placed as shown in figure 20 for a one-lane ramp. For dual-lane exit ramps, a separate identical detection system and warning sign is used in the second lane with the system connected into one controller.

Detection stations 1 and 2, loop-piezo-piezo (class 1) configurations, will provide weight, vehicle classification, and vehicle speed to the programmable controller. (Based on suggestions from the two State agencies, the original design concept was changed to collect truck classification/speed/weight at both stations in order to provide redundancy and increase accuracy.) Data on vehicle height will be provided by the height detector, which is placed near station 2, to the programmable controller. The data from stations 1 and 2 and the height detector will be analyzed by the programmable controller to determine if the vehicle is or will exceed a critical speed at the point of curvature. If the controller determines that the vehicle will exceed the critical speed at the point of curvature, given its entry speed, weight, vehicle classification, and ramp geometrics, the controller will activate a warning information system, i.e., a readable message on a fiber-optic sign mounted below a static warning sign as previously shown in figure 11. Detection station 3 will consist of a loop-piezo-loop (Class 2) configuration and will be used to collect vehicle speed at the PC on the ramp. This third detection system is for evaluation purposes to determine the speed reduction of trucks with or without a sign activation.

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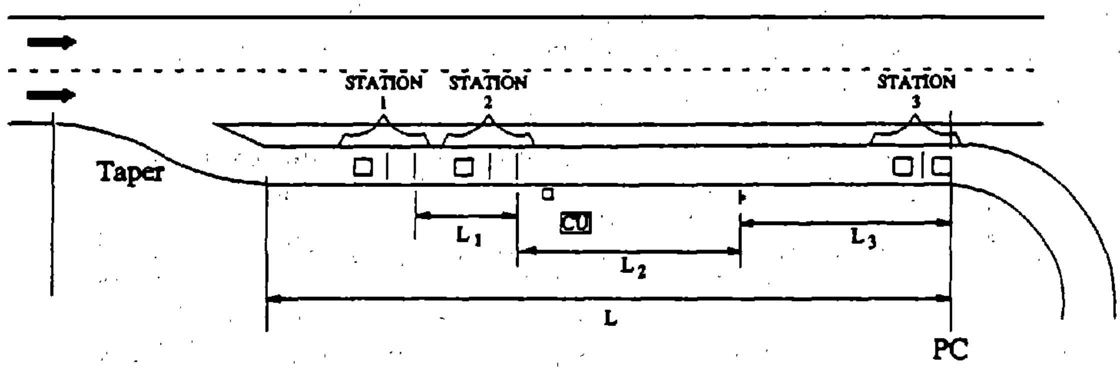

$\boxed{CU}$	=	Controller Unit.
□	=	Height Detector.
	=	Warning Sign.
L	=	Length of ramp deceleration lane.
L_1	=	Distance between Station 1 and Station 2 equals 100 ft (30.5 m).
L_2	=	Distance between Station 2 and Warning Sign equals 200 ft (61.0 m).
L_3	=	$\dfrac{V_1^2 - V_2^2}{2d}$ where V_1 is mainline speed limit, V_2 is critical ramp speed, and d is deceleration.
PC	=	Point of Ramp Curvature.

Figure 20. Typical automatic truck warning system detector placement for one-lane ramp.

The operation logic for this system is shown in figure 21 and is described as follows. Both detection stations 1 and 2 will provide weight, vehicle classification, and vehicle speed to the programmable controller. If the vehicle is classified as a truck, the two weights will be compared and the heavier weight will be used. Also, at station 2, a height detector will determine if the truck is less than 11 ft (3.4 m), and if so, it will be classified as a tanker truck. Depending upon whether the truck is classified as a tanker or non-tanker, then a rollover threshold value will be assigned to it based on its weight using the following data programmed into the controller:

TANKER		NON-TANKER	
Weight Range (lb)	RT	Weight Range (lb)	RT
0 - 10K	0.65g	0 - 35K	0.73g
>10K - 20K	0.50g	>35K - 50K	0.60g
>20K - 50K	0.49g	>50K - 65K	0.50g
>50K - 70K	0.34g	>65K - 80K	0.38g
>70K - 80K	0.26g	>80K - 100K	0.36g

1 lb = 0.454 kg

- From station 1 and station 2 detectors, the truck's deceleration (d) will be determined from the following equation:

$$d = \frac{V_1^2 - V_2^2}{2L_1} \tag{10}$$

where V_1 and V_2 are speeds at stations 1 and 2, respectively, and L_1 is the distance between them, established at 100 ft (30.5 m).

- Based on deceleration rate d from above, the likely speed of the truck at the point of curvature is calculated as follows:

$$V_{PC} = \sqrt{V_2^2 - 2 \cdot d \cdot (L_2 + L_3)} \tag{11}$$

where $(L_2 + L_3)$ is the distance from the second station to the point of curvature.

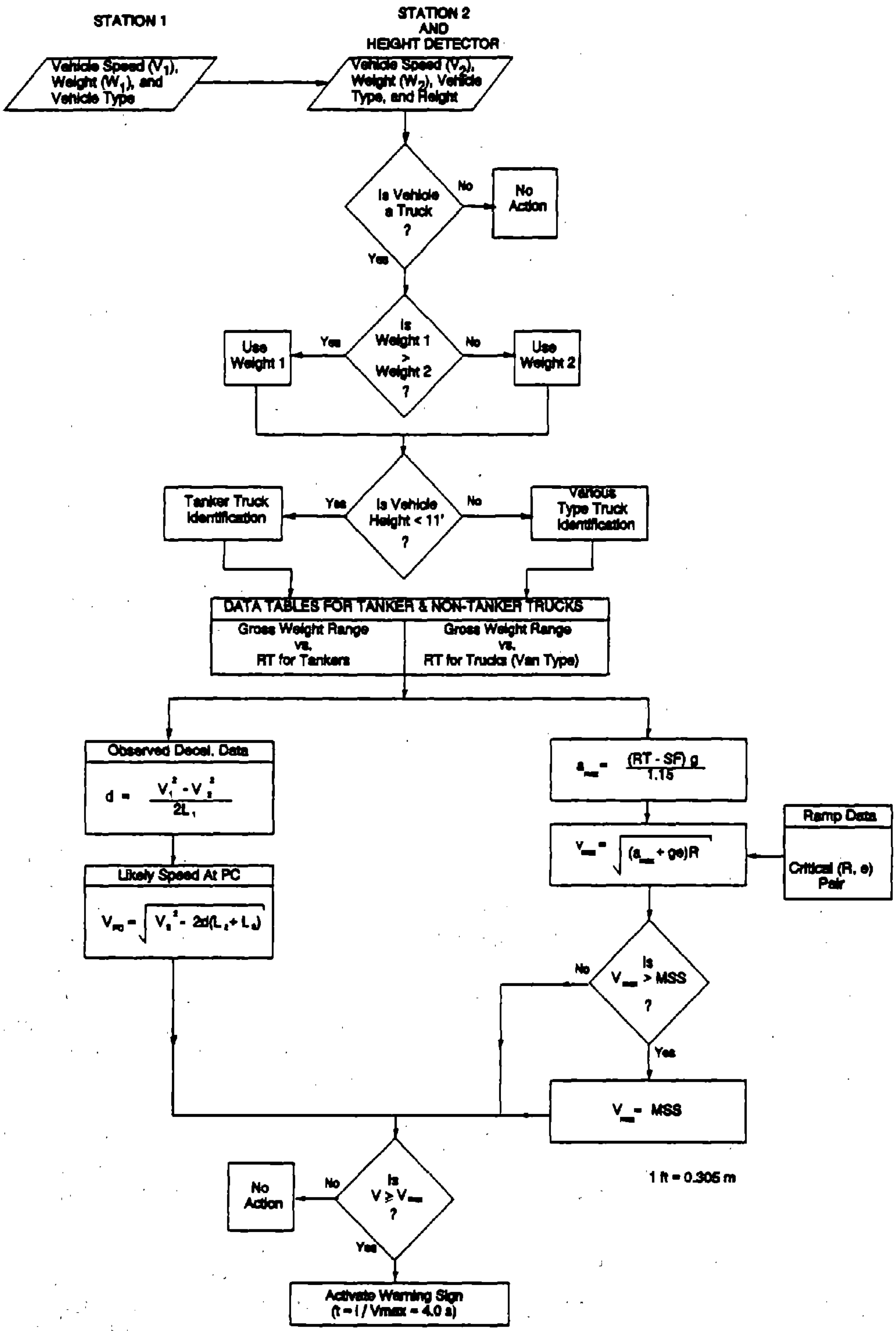

Figure 21. Operational logic for activating the warning system.

- The maximum value of lateral acceleration a_{max} beyond which the truck will rollover is calculated as follows:

$$a_{max} = \frac{(RT - SF)g}{1.15} \tag{12}$$

- The maximum rollover threshold speed (V_{max}) is then calculated from the following:

$$V_{max} = \sqrt{(a_{max} + ge)\ R} \tag{13}$$

- The calculated V_{max} is then compared to a maximum safe speed (MSS), which is determined by the user and would normally be set at about 60 mi/h (96.6 km/h). The lower of the two values is used in the next step.

- The likely speed at the PC, calculated previously as V_{PC}, is then compared to the V_{max}. If it is equal to or greater than V_{max}, then the sign is activated.

At station 3, the vehicle speed for the truck is also measured. Data from all stations are recorded and retained in the controller for a specified period. The data can be downloaded to a microcomputer at the controller site or transferred to a microcomputer in a central office over a communication link.

System Costs

System B costs were estimated initially at about $80,000 for a one-lane installation based on the preliminary design. This estimate was updated based on the final designs prepared for the three ramps and actual bids from an equipment provider and an installer contractor. Table 6 provides a summary of the cost elements for installing the system B design at the three ramps. Detailed cost data are shown in appendix B. The controller modification cost of $22,500 is a quote from a manufacturer of a WIM system to modify their controller to meet the requirements of this system. This development cost is a one-time cost for the three projects and presumably would not be a cost if the system were to be installed at a significant number of locations.

The construction costs vary for the three sites. Ramps 2 and 3 are for dual-lane installations and their average cost is about $185,000. Based on these three installation cost estimates, the construction cost for a typical one-lane installation would be $104,000 and for a two-lane installation about $185,000.

In addition to the construction cost, there is an approximate $5,000 per site cost for system calibration, commissioning, and testing. This would bring the installation cost up to $109,000 and $190,000 for a single-lane and dual-lane system, respectively. The operator training cost shown in table 6 is not a per site installation cost. For this cost-effectiveness analysis, it is assumed that the per site cost would be $1,000. The final cost for installation, not shown in table 6, is the engineering design costs. Based on the designs for the three sites, this is estimated at $10,000 and $15,000 for single- and dual-lane installations, respectively. In summary, the total design and installation costs are as follows:

- Single-lane ramp - $121,000.
- Dual-lane ramp - $206,000.

Annual maintenance and operation costs are estimated at about $1,000 per year. This allows for inspection, reduction of data from the controller, etc. With proper installation, the system should have a service life of at least 10 years.

Table 6. Automatic truck rollover warning system total estimated cost for three sites.

Cost Item	Total Estimated Cost ($)[1]
Controller Modifications	$22,500
Construction Cost	
Ramp 1 (I-495W/RT 123 VA)	104,000
Ramp 2 (I-95S/I-95S VA)	177,000
Ramp 3 (I-495E/I-95N MD)	193,000
System Calibration, Commissioning, and Testing Cost ($5,000 per ramp x 3)	15,000
Operators Training Costs ($2,000 per State x 2 States)	4,000
Total	$515,500

[1] See appendix B for detailed cost breakdown.

Benefit Costs

The benefits from this automatic warning system are a reduction in truck rollover accidents and the associated costs. Specifically, the costs are the dollar values assigned to the resulting fatalities, injuries, vehicle property damage, and cargo loss; the possible damage to the highway facility and appurtenances; the cost imposed on the motorist delayed by the accident; and the cost of traffic control and cleanup.

Truck accidents can be very costly, especially if hazardous cargo is involved. For instance, a truck rollover accident that occurred at a Capital Beltway interchange and involved a fuel tanker truck, resulted in a fatality, substantial structural damage to the bridge overpass due to fire, and enormous delay and vehicle operating costs to motorists caused by the 3-hour blockage of the Beltway. A study of truck accidents on urban freeways presented accident cost data that indicates that the average total cost of a truck accident is $13,274.[19] This value is based on the reported $634,000 per freeway mile ($394,000 per freeway kilometer) cost (considering all the cost elements discussed above for 2,221 reported accidents over 46.5 miles (74.9 km) of freeway).

Another estimate of the cost of a truck accident was found in a study of the Washington Bypass.[20] In that study, an analysis of truck accidents on the Capital Beltway was performed and a cost per accident was established. Applying the observed distribution of accidents by severity for truck accidents on the Beltway for 1986 to 1987, the costs per accident type of $1,200,000 per fatality, $13,650 per injury, and $2,425 per property damage only (PDO) accident, a $15,470 per accident value was developed. This value did not include any delay costs or cleanup costs.

Both of the values cited above – $13,274 and $15,470 – are likely to be less than the average costs of a truck rollover accident. A more likely average is estimated at $20,000 with a significant probability that a given accident of this type could result in a fatality.

Cost-Effectiveness Analysis

One way to assess the cost-effectiveness of an automatic truck warning system is to establish how many accidents would have to be eliminated by the system to make it "pay for itself." Table 7 provides the results of this type analysis. Increments of total accident costs ranging from the estimated average costs of $20,000 to $1,000,000 are listed with the number of accidents that would have to be eliminated by a one-lane or two-lane system. The system costs are those installation costs identified earlier, plus a $1,000 per year cost for maintenance over the 10-year life. The analysis revealed that a single lane system would have to eliminate nearly seven accidents, resulting in an average of $20,000 total costs, in 10 years. However, if the average rollover accident was to result in $100,000 of economic loss, then the elimination of two accidents in 10 years would more than pay for the system. For a two-lane system, nearly 11 accidents averaging $20,000 in costs would have to be eliminated in 10 years.

Table 7. Required rollover accident reduction for system cost-effectiveness.

All Accident Costs ($)	No. of Rollover Accidents	
	One-Lane System @$131,000[1]	Two-Lane System @$216,000[1]
20,000	6.55	10.80
50,000	2.62	4.32
100,000	1.31	2.16
500,000	0.26	0.43
1,000,000	0.13	0.22

[1] Installation costs plus $1,000 per year for 10 years for maintenance.

Obviously the cost-effectiveness of this system is very much dependent on whether or not it prevents the high cost rollover accident – an event which is relatively rare. Referring back to the truck rollover occurrence data in table 2, there were 12 rollover accidents at 7 ramps in Virginia over a 4-year period. A linear extrapolation of this frequency rate would reveal that there could be an average of 4.25 accidents per ramp for those 7 ramps. Hence, it appears from this simplistic, but reasonable, analysis that an effective automatic truck warning system could be cost-effective if applied at ramps with a history of truck rollover accidents of at least one every 5 years.

APPENDIX A. VIDEO SENSOR SYSTEM[1]

INTRODUCTION

This document is intended to concisely present the current status of video image processing research and applications, as it pertains to the project, "Feasibility of an Automatic Truck Warning System." Specifically, the issue of using image processing techniques to identify the various truck types is addressed. First, the basic principles of image processing are briefly described. Applications of image processing technologies that are of relevance to the issue of vehicle classification are discussed next. Two approaches to classifying trucks using image processing technologies in the environment of the automatic warning system are then suggested. Finally, some issues of particular importance are portrayed.

The primary sources for the information presented here are previous studies that were conducted in the University of Michigan Transportation Research Institute (UMTRI) to address the feasibility of employing image processing technologies for Intelligent Vehicle-Highway Systems (IVHS) and an experimental system that was developed at UMTRI.

IMAGE PROCESSING - BASIC PRINCIPLES

A typical image processing system flow is shown in figure 22. The video display, which is the screen with which the user interacts, and the video storage are used in developing and checking the system, but they are not necessary to perform the image processing. Since the computers that are used to process the data (which is the image in this case) are digital, the video signal from the camera needs to be digitized. The digital signal is then processed to filter and remove the unnecessary background data and to identify the objects of interest. Analysis of these selected objects is then performed according to the desired output of the processing algorithm.

The hardware layout commonly used in image processing is illustrated in figure 23. Again, the video display and storage (connected with a dotted line) are not essential to perform the task of processing the video image. Such a layout is typical when one's approach is to develop and/or evaluate the feasibility of concepts (which is commonly the case in today's applications of video image processing technologies). When installing a system designed to operate on a permanent basis, speed, resolution, and efficiency call for eliminating the link that takes the charge couple device (CCD) output through the RS-170 and the digitizer card (figure 24). In that case, custom hardware (a "custom-

[1]Prepared by Zevi Bareket.

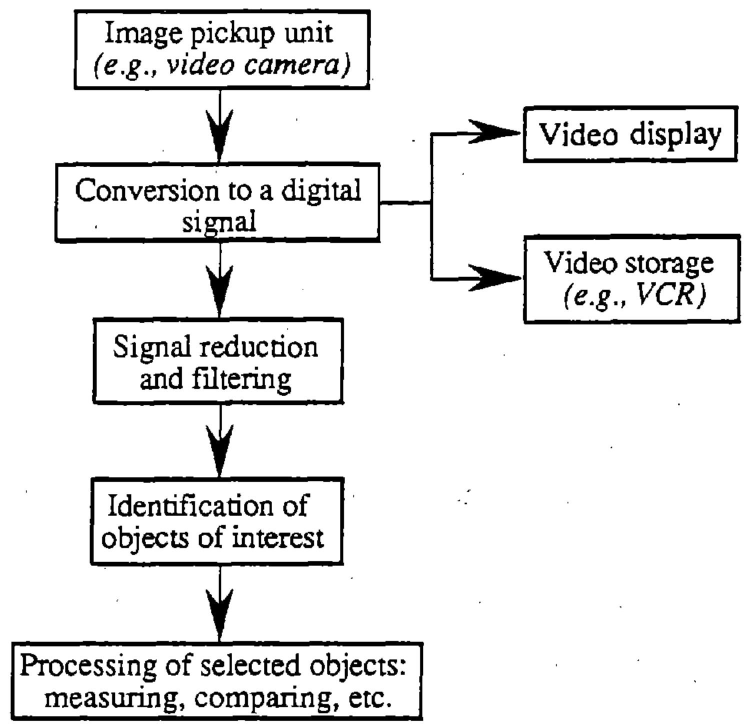

Figure 22. Image processing - typical flow.

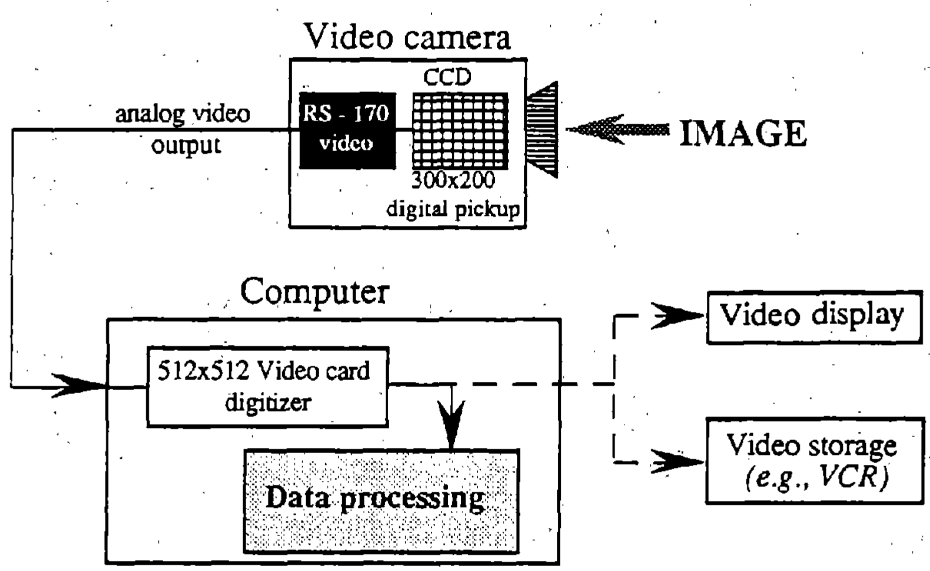

Figure 23. Hardware layout.

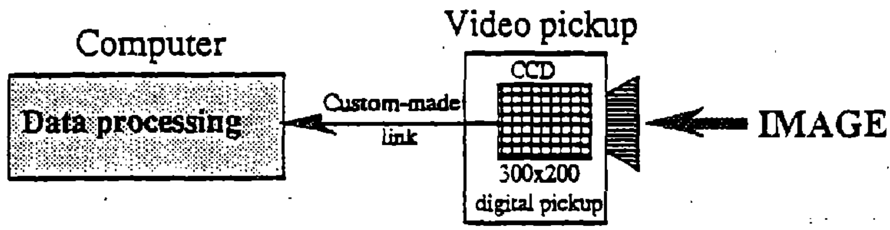

Figure 24. Hardware layout - permanent system.

made link" in figure 24) needs to be developed to communicate between the CCD pickup unit and the data processing computer.

IMAGE PROCESSING APPLICATIONS AND RESEARCH

Image processing, as described in the literature, is used almost exclusively for purposes of either autonomous vehicle navigation, or vehicle detection and counting. According to the available publications, it is not being used (at least not as a working system, even experimentally) for vehicle classification purposes in real time. Some studies have taken an initial look into this issue and the feasibility of using video-captured images to classify vehicles, but not to the extent of practically setting up an outdoor full-scale system.[21] Furthermore, these studies were aimed to distinguish only between primary classes of vehicles (i.e., passenger cars, trucks, etc.). For the purpose of an automated rollover warning system, a much finer classification is required for identifying van-trailers, tankers, flat-beds, etc.

In an Australian study, an attempt has been made to utilize image processing to classify vehicle types.[21] A line scan array camera is being used to analyze scaled-down vehicle models. A lighting source (floodlight) is positioned behind the passing models to provide adequate illumination. To reduce the amount of data being collected and analyzed, the cameras captured only samples of the cross section (i.e., only those sections of its side view that were located at predetermined, fixed intervals along its length).

The captured image is processed to provide information about length and height. These parameters are used to classify the type of vehicle (car, truck, etc.).

The study is described as "first stage of practical realization" of vehicle classification by means of video imaging, and states that further study and development is required to assess the feasibility of such methods.

In a review study of current developments pertaining to IVHS worldwide, several new technologies are discussed.[22] With regard to video image processing, four tasks are referred to as accomplished with some level of success:

- Loop emulation – Variations in a video image can be used to detect objects (vehicles in this case). The camera "looks" at some spot continuously, and when a big enough "blob shows up," it is registered as a vehicle. The system described in reference 22 uses video image processing to emulate a loop detector.

- Vehicle tracking – Provides time-position trajectories for vehicles crossing the monitored scene.

- Lane monitoring – Provides tracking of traffic flow on multilane roads and locates queues.

- Vehicle classification – Only primary type classification is discussed (i.e., car, bus, truck, etc.) as in reference 21. In addition, due to the fact the classification/ identification needs to be done in real time on the one hand, and that it requires processing of a large amount of data on the other hand, most approaches are not feasible for rollover warning.

Another study aimed at assessing development efforts pertaining to image processing underway in both Europe and the U.S., was conducted by the Canadian Ministry of Transportation.[23] In Europe, the U.K. is considered the leader in image processing (within "PROMETHEUS"). The vision system developed (IPL 5000) is aimed at recognizing characters on the license plates of vehicles for purposes of identification, traffic volume assessment, travel time measurement, and surveillance. A similar system (RIA-300) for deciphering characters on license plates was developed in the U.S. by the 3-M company. Saab-Scania is working on an invehicle image processing system to interpret roadside speed signs. The goal of this system is to alert the driver about speed limits while his attention is focused on the road. Other image processing systems under development (like the one described in reference 24 and the one being developed by GTL and Porsche) are also mentioned.

An experimental real-time system that utilizes video imaging to detect traffic is described in reference 24. It uses an array of cameras to monitor spots in an intersection, with the ability of each camera to monitor more than one spot. Presence and passage of an object over the observed spots are detected and processed to determine if it is a vehicle, and what its speed is. As mentioned before, elimination of the background and treating the remaining entities as objects of interest, are fundamental to image processing. Some weather elements like rain, fog, and snow, and especially light reflections or shadows cast by passing objects, are therefore often surmised by the system as objects of interest. When misdetections occurred, they were mainly due to such weather conditions and shadows.

Dr. Panos Michalopoulos of the University of Minnesota gave his perspective on the feasibility of incorporating image processing technologies into the rollover warning system, and the role that the experimental system described above can have in that context. He could not point out any published study (not to mention a working system) that is aimed at facilitating video image processing for vehicle identification. Some English groups are conducting a rather intensive investigation, though.

The experimental system installed in Minnesota is capable of measuring speed, length, and count (volume) of the passing vehicles. The system as currently installed costs about $30,000 and uses four video cameras. It is capable of processing the data collected from the four cameras in real time, simultaneously. It cannot classify vehicles into distinct types, but the system can be expanded (at significant expense and development time) to perform the desired task of vehicle identification and classification. As an example of added hardware cost, Michalopoulos addressed the cameras: the present ones are slow, since the objective of the system in its current configuration is traffic counting only. To identify the vehicle, a much more detailed picture is required, so the cameras should be special high speed ones. With regard to maintenance and durability, no special problems have been experienced during the operation of the system so far. If the proper installation procedures for these outdoor cameras are followed, their expected life is about 10 years. For "ballpark" estimation, if it needs to be replaced, a camera costs several hundred dollars. Obviously, the cameras involved in a vehicle identification system are expected to be much more expensive.

A process for real-time recognition is described in reference 25. The classification is according to basic categories (in this study an attempt is made to discriminate between cars and vans), and it is performed using templates. These templates are outlines of captured images, about 32 x 32 bits. They are generated by "subtracting" (removing) the road background image from the road active image, and applying filtering to "clean" the noise. During the classification process, outlines of passing vehicles are matched with the templates to determine the type of vehicle detected. After proper filtering, when cars were compared to a van template, the algorithm was correct 86 percent of the time. The study concludes that filtering is an important factor in achieving accurate recognition, and several matches should be made in a complete system to improve the matching and classification process.

In a recent study conducted by UMTRI, an experimental image processing system was developed. The goal of that system is to use video images captured by a camera overlooking a road section (a four-way junction in this case), identify vehicles as they enter the intersection, and produce a "computerized outline" of each vehicle (a rectangle that defines the image's location). These outlines were then used to track the motion of the vehicle throughout the camera's field of view, while analyzing its dynamic control inputs and characteristics (steer angle, yaw rate, acceleration, etc.). Kalman filtering was used for that analysis. The generated trajectories can also be used to study interactions between vehicles, or as a generic traffic environment for the purpose of developing an onboard crash avoidance system.

IMAGE PROCESSING AS PART OF THE AUTOMATIC TRUCK WARNING SYSTEM

Within the framework of the automated truck rollover warning system, video image processing can be utilized to:

- Distinguish between specific, pre-defined configurations that other data acquisition systems cannot handle. Usually, such a discrimination involves visual cues. Tanker trailer vs. van trailer is a typical (and a viable) example.
- Acquire "outline" geometric data of the vehicle, i.e., total length, total height.
- Acquire more detailed geometric data of the vehicle. These additional details span in their complexity from counting axles, through counting units, up to a complete profile mapping of the vehicle. Level and complexity of equipment used will determine how detailed the acquired geometric data might be.
- Classify vehicles and identify types. This is the most sophisticated application of image processing in the context of the warning system. Again, the classification scale is wide and depends on the complexity of the equipment used.

The following discussion addresses two approaches: One is a simplified approach that is aimed at detecting distinct, pre-defined types with unique characteristics from the rest of the traffic (first bulleted item above). The second is a sophisticated, "intelligent" system (fourth bulleted item) that is based on technologies designed to "learn and deduct" as they operate (i.e., "neural-networks"). Utilization of image processing as described under the second or third item will employ an intermediate development level between the simplified and the sophisticated approaches.

Simplified Approach

This approach is goal-oriented. It is aimed at executing a well-defined, narrow task. In the case of the automatic rollover system for example, one might be concerned about identifying tankers. Unlike the flat sidewall of the van type of trailer, the tanker has a curved shape. By positioning two video pickup units aimed towards the side of the trailer, a stereopsis three-dimensional image is captured. To avoid the slow rate of processing associated with stereopsis, only three points need to be evaluated to determine if they conform to some curvature shape (tanker), flat (van), or some arbitrary arrangement (flat-bed). Stereopsis video vision as used for autonomous vehicle navigation is described in reference 26.

Sophisticated Approach

The most advanced image processing interpretation methods today incorporate "neural-network" technologies. Such a system (like other artificial intelligence technologies) attempts to mimic the deduction algorithm according to which the human brain interprets inputs and deduces conclusions. A possible layout of the video image processing, pertaining to an automatic rollover warning system, is shown in figure 25.

Initially, the system needs to be "introduced" to the various prototypes. By displaying different variations of each prototype, the network "learns" how to classify and process new images, and determine which variations around some basic configuration of vehicle are still to be considered as the same configuration (phrased as "acceptable tolerance" in figure 25). By means of back propagation of observations and feed-forward outputs, the system learns and accumulates "experience" continuously.

ISSUES OF PARTICULAR CONCERN/CONCLUDING POINTS

- Shadows -- During the day as the sun moves, and under artificial lighting at night, shadows cast by the vehicle will be considered as part of the image by the video unit. Positioning angles of the equipment and lighting should be carefully considered.

- Lighting -- The scene needs to be well illuminated for the video to get all the details. That illumination can be either normal white light, laser scanning beam, or infrared. The advantage of the laser is that the exact area to be processed can be highlighted, while significantly reducing shadow effects. A disadvantage of the laser is public rejection and misconceptions about lasers, including even eye-safe lasers.

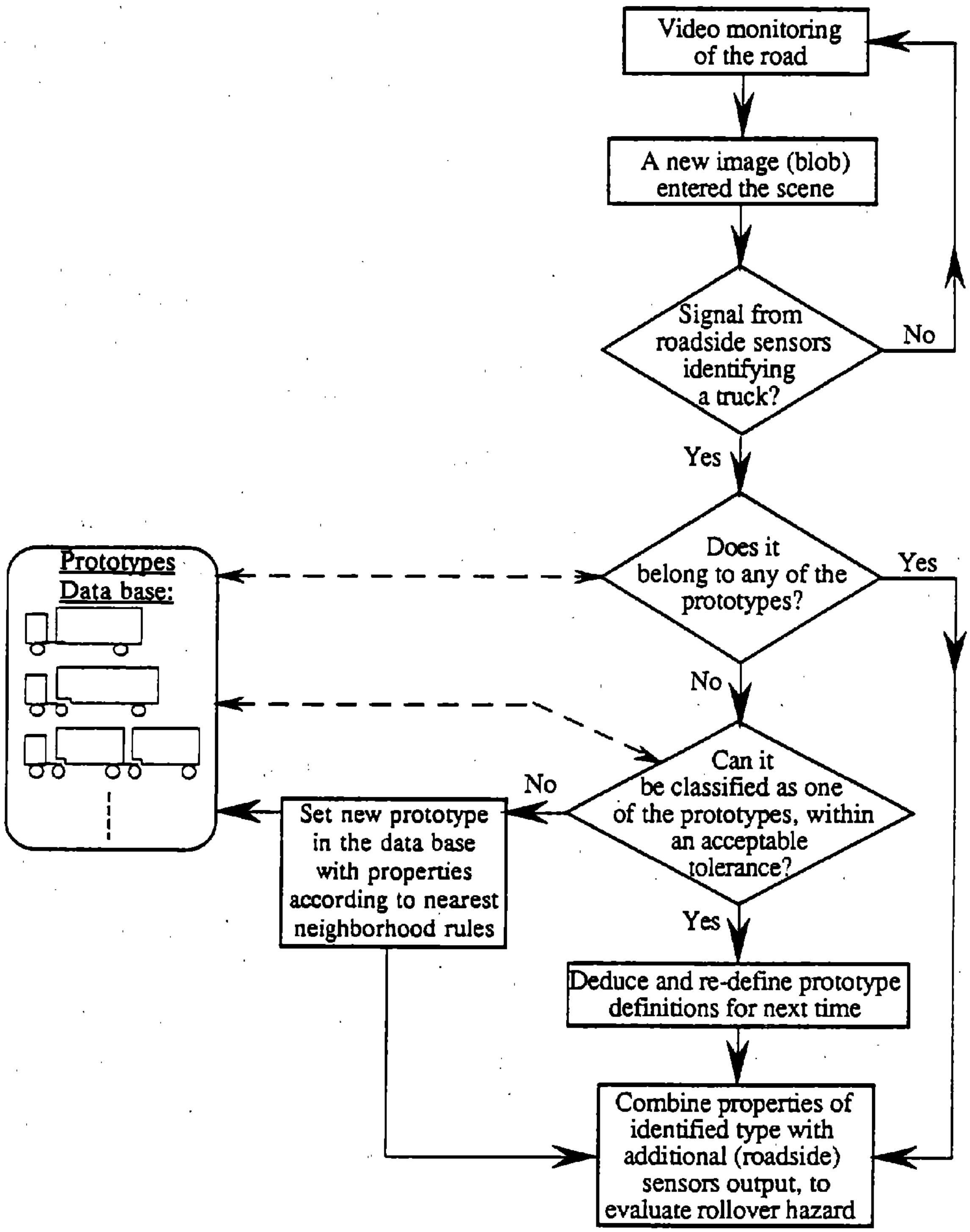

Figure 25. Vehicle classification with neural network.

- Custom hardware – Some items that are designated to be used as parts of such a system still need to be developed. Communication means as described in association with figure 25 should be dedicated, and are not available as "off-the-shelf" items.

- Accuracy and cost – These two closely related items depend upon each other. The desired level of accuracy will determine how costly the system will be. The cheapest application of image processing for this work would probably be the simplified approach described above. It would provide only truck/van/flat-bed kind of discrimination. It will not count the number of trailing units, or compute the length of the truck. Accuracy limitations for such a system might lead to errors such as misidentification of a flat-bed carrying a big pipe as a tanker, for example.

- Positioning of cameras – As described above, the main approach for separating the items of interest from the rest of the image is by canceling the background from the image containing the vehicle. If the camera is positioned on less-than-stable mounts that vibrate or swing, the image that the system defines as background at one instant, is no longer valid at the next one, when the vehicle shows up. Another positioning aspect might be the angle – it affects the shadows as mentioned above, and it also might contain background traffic that is not part of the true background that should be removed from the image with the analyzed vehicle.

APPENDIX B. COST ESTIMATES FOR CONSTRUCTION OF WARNING SYSTEM AT THREE SITES

Table 8. One-lane system construction cost for Virginia site I-495/Rte. 123N.

Item	Unit Spec.	Qty	Unit Material Cost	Labor Cost To Install Per Unit	Total Installation Cost Per Unit	Total Cost
Programmable Classifier w/24-h Uninterrupted Power Supply (UPS) and 9600 Modem	EA.	1	$13,150	$2,000	$15,150	$15,150
Host Computer	EA.	1	4,000	500	4,500	4,500
Magneto Optical Disk	EA.	1	5,100	500	5,600	5,600
Small Single-Door Enclosure (NEMA 3R)	EA.	1	-	-	75	75
Narrow Beam Detector Sensor	EA.	1	695	1,000	1,695	1,695
Permanent Piezoelectric Sensor-Class 1	EA.	4	1,750	1,000	2,750	11,000
Permanent Piezoelectric Sensor-Class 2	EA.	1	515	1,000	1,515	1,515
Piezoelectric Sensor Amplifier	EA.	1	500	200	700	700
RG-58 Cu Cable For Piezo Sensors	L.F.	1090	1.50	1.50	3.00	3,270
8/2 Electrical Conductor Cable	L.F.	15	-	-	3.00	45
14/1 Electrical Conductor Cable	L.F.	540	-	-	2.50	1,350
14/2 Electrical Conductor Cable (S)	L.F.	1440	-	-	1.50	2,160
14/2 Electrical Conductor Cable	L.F.	310	-	-	1.45	450
10/3 Electrical Conductor Cable	L.F.	345	-	-	1.80	621
14/4 Electrical Conductor Cable	L.F.	25	-	-	1.75	44
1" Metal Conduit (Signal)	L.F.	180	-	-	8.00	1,440
1 " Metal Conduit	L.F.	10	-	-	7.00	70
2" Conduit (Signal)	L.F.	825	-	-	4.00	2,682
2" Metal Conduit	L.F.	30	-	-	5.50	165
3" Conduit (Signal)	L.F.	30	-	-	3.75	113
Trench Excavation	L.F.	865	-	-	10.00	8,650

1 in = 25.4 mm   EA. = each
1 ft = 0.305 m   L.F. = linear feet

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Table 8. One-lane system construction cost for Virginia site I-495/Rte. 123N (Continued).

Item	Unit Spec.	Qty	Unit Material Cost	Labor Cost To Install Per Unit	Total Installation Cost Per Unit	Total Cost
Saw Cut 1/4"	L.F.	80	-	-	$7.00	$ 560
Saw Cut 5/8"	L.F.	180	-	-	6.50	1,170
Saw Cut 1-3/4"	L.F.	60	-	-	6.00	360
Traffic Cabinet and Foundation (CF-2)	EA.	1	-	-	3,500	3,500
Signal Junction Box (JB-1A, 1B, or 1C)	EA.	2	-	-	385	770
Signal Junction Box (JB-5A, 5B, or 5C)	EA.	3	-	-	535	1,605
Sign Post Steel 5" x 3" x 3/8" x 20'	EA.	1	-	-	200	200
Electrical Service (SE-5)	EA.	1	-	-	450	450
Pedestal Pole PF-2 5'	EA.	1	-	-	600	600
Concrete Foundation PF-2	EA.	1	-	-	550	550
Concrete Foundation PF-3	EA.	1	-	-	450	450
Type B, Class I, Pavement Marking 6"	L.F.	250	-	-	.20	50
Sign Assembly:						
1. Fiber Optic Sign	EA.	1	-	-	12,395	12,395
2. Static Sign Panel	S.F.	36	-	-	410	410
3. Steel Sign Post 14'	L.F.	45	-	-	2,012	2,012
4. Foundations (SSP-VIA)	EA.	2	-	-	2,520	2,520
Subtotal						17,337
Work Zone Traffic Control	L.S.	-	-	-	-	15,000
Total Construction Cost						**$103,897**

1 in = 25.4 mm
1 ft = 0.305 m
1 ft^2 = 0.09 m^2

EA. = each
L.F. = linear feet
L.S. = lump sum
S.F. = square feet

Table 9. Two-lane system construction cost for Virginia site I-495W/I-95S.

Item	Unit Spec.	Qty	Unit Material Cost	Labor Cost To Install Per Unit	Total Installation Cost Per Unit	Total Cost
Programmable Classifier w/24-h Uninterrupted Power Supply (UPS) and 9600 Modem	EA.	1	$13,150	$2,000	$15,150	$15,150
Narrow Beam Detector Sensor	EA.	2	695	1,000	1,695	3,390
Permanent Piezoelectric Sensor-Class 1	EA.	8	1,750	1,000	2,750	22,000
Permanent Piezoelectric Sensor-Class 2	EA.	2	515	1,000	1,515	3,030
RG-58 Cu Cable For Piezo Sensors	L.F.	2730	1.50	1.50	3.00	8,190
8/2 Electrical Conductor Cable	L.F.	15	-	-	3.00	45
14/1 Electrical Conductor Cable	L.F.	1180	-	-	2.50	2,950
14/2 Electrical Conductor Cable (S)	L.F.	2190	-	-	1.50	3,285
10/3 Electrical Conductor Cable	L.F.	445	-	-	1.80	801
14/4 Electrical Conductor Cable	L.F.	440	-	-	1.75	770
1" Metal Conduit (Signal)	L.F.	155	-	-	8.00	3,745
1 " Metal Conduit	L.F.	10	-	-	7.00	70
2" Conduit (Signal)	L.F.	535	-	-	4.00	2,140
2" Metal Conduit	L.F.	645	-	-	5.50	3,548
4" Conduit Signal	L.F.	15	-	-	3.50	53
Jacked Pipe 4"	L.F.	45	-	-	65.00	2,925
Trench Excavation	L.F.	550	-	-	10.00	5,500
Saw Cut 1/4"	L.F.	170	-	-	7.00	1,190
Saw Cut 5/8"	L.F.	420	-	-	6.50	2,730
Saw Cut 1-3/4"	L.F.	110	-	-	6.00	660

1 in = 25.4 mm
1 ft = 0.305 m

EA. = each
L.F. = linear feet

Table 9. Two-lane system construction cost for Virginia site I-495W/I-95S (Continued).

Item	Unit Spec.	Qty	Unit Material Cost	Labor Cost To Install Per Unit	Total Installation Cost Per Unit	Total Cost
Traffic Cabinet and Foundation (CF-2)	EA.	1	-	-	$3,500	$3,500
Signal Junction Box (JB-1A, 1B, or 1C)	EA.	2	-	-	385	770
Signal Junction Box (JB-5A, 5B, or 5C)	EA.	5	-	-	535	2,675
Tubular Rect. Sign Post Steel 5" x 3" x 3/8"	EA.	2	-	-	200	400
Electrical Service (SE-5)	EA.	1	-	-	450	450
Pedestal Pole PF-2 5'	EA.	1	-	-	600	600
Concrete Foundation PF-2	EA.	1	-	-	550	550
Sign Assembly:						
1. Fiber Optic Sign	EA.	2	-	-	24,790	24,790
2. Static Sign Panel	S.F.	72	-	-	820	820
3. Steel Sign Post 14'	L.F.	90	-	-	4,023	4,023
4. Foundations (SSP-VIA)	EA.	4	-	-	5,040	5,040
Subtotal						34,673
Guardrail Beam (GR-2)	L.F.	338	-	-	42.00	14,196
Fixed Object Attachment GR-FOA-2	EA.	2	-	-	30.00	60
Relocation Existing Sign	EA.	2	-	-	1,000	2,000
Work Zone Traffic Control	L.S.	-	-	-	--	35,000
Total Construction Cost						**$177,046**

1 in = 25.4 mm
1 ft = 0.305 m
1 ft² = 0.09 m²

EA. = each
L.F. = linear feet
L.S. = lump sum
S.F. = square feet

Table 10. Two-lane system construction cost for Maryland site I-495E/I-95N to Baltimore.

Item	Unit Spec.	Qty	Unit Material Cost	Labor Cost To Install Per Unit	Total Installation Cost Per Unit	Total Cost
Programmable Classifier w/24-h Uninterrupted Power Supply (UPS) and 9600 Modem	EA.	1	$13,150	$2,000	$15,150	$15,150
Host Computer	EA.	1	4,000	500	4,500	4,500
Magneto Optical Disk	EA.	1	5,100	500	5,600	5,600
Small Single-Door Enclosure (NEMA 3R)	EA.	2	-	-	75	150
Narrow Beam Detector Sensor	EA.	2	695	1,000	1,695	3,390
Permanent Piezoelectric Sensor-Class 1	EA.	8	1,750	1,000	2,750	22,000
Permanent Piezoelectric Sensor-Class 2	EA.	2	515	1,000	1,515	3,030
Piezoelectric Sensor Amplifier	EA.	2	500	200	1,400	1,400
RG-58 Cu Cable For Piezo Sensors	L.F.	5450	1.50	1.50	3.00	16,350
14/1 Electrical Conductor Cable	L.F.	950	-	-	2.50	2,375
14/2 Electrical Conductor Cable (S)	L.F.	2875	-	-	1.50	4,313
14/2 Electrical Conductor Cable	L.F.	44	-	-	1.45	64
10/3 Electrical Conductor Cable	L.F.	605	-	-	1.80	1,089
14/4 Electrical Conductor Cable	L.F.	830	-	-	1.75	1,453
8/3 Electrical Conductor Cable	L.F.	800	-	-	3.50	2,800
Telephone Cable (2-wire)	L.F.	780	-	-	2.00	1,630
1" Galvanized Conduit (Signal)	L.F.	90	-	-	8.00	720
1¼" Galvanized Conduit	L.F.	20	-	-	7.00	140
2" Conduit (Trenched)	L.F.	1605	-	-	4.00	6,420
2" Conduit in Jacked Pipe	L.F.	225	-	-	4.00	900
2" Galvanized Conduit (Trenched)	L.F.	685	-	-	5.50	3,795
2" Galvanized Conduit in Jacked Pipe	L.F.	80	-	-	5.50	440
2" Galvanized Conduit (attached to concrete wall and pole)	L.F.	15	-	-	5.50	83
3" Galvanized Conduit	L.F.	435	-	-	5.00	2,175

1 in = 25.4 mm EA. = each
1 ft = 0.305 m L.F. = linear feet

Table 10. Two-lane system construction cost for Maryland site I-495E/I-95N to Baltimore (Continued).

Item	Unit Spec.	Qty	Unit Material Cost	Labor Cost To Install Per Unit	Total Installation Cost Per Unit	Total Cost
Jacked Pipe 4"	L.F.	90	-	-	$65.00	$5,850
Jacked Pipe 5"	L.F.	130	-	-	70.00	9,100
Saw Cut 1/4"	L.F.	100	-	-	7.00	700
Saw Cut 5/8"	L.F.	300	-	-	6.50	1,950
Saw Cut 1-3/4"	L.F.	110	-	-	6.00	660
Traffic Cabinet	EA.	1	-	-	2,500	2,500
Metal Traffic Barrier	L.F.	405	-	-	42	17,010
End Flares	EA.	3	-	-	100	300
Precast Concrete Handbox	EA.	16	-	-	500	8,000
Sign Post Steel 5" x 3" x 3/8" x 20'	EA.	2	-	-	200	400
Sign Post Wood 4" x 4" x 5" x 5'	EA.	2	-	-	200	400
Meter Socket and Disconnect Switch	EA.	1	-	-	500	500
Ground Rod	EA.	5	-	-	10	50
Concrete Foundation	CY.	1.63	-	-	1,250	1,250
Sign Assembly:						
1. Fiber Optic Sign	EA.	2	-	-	24,790	24,790
2. Static Sign Panel	EA.	2	-	-	820	820
3. Steel Sign Supports	PAIR	2	-	-	4,023	4,023
4. Foundations	PAIR	2	-	-	5,040	5,040
Subtotal						34,673
Work Zone Traffic Control	L.S.	-	-	-	-	30,000
Total Construction Cost						**$193,342**

1 in = 25.4 mm
1 ft = 0.305 m
1 yd³ = .76 m³

EA. = each
L.F. = linear feet
C.Y. = cubic yards
L.S. = lump sum

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